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EVALUATION OF DATA COMPRESSION TECHNIQUES FOR RADAR LANDMASS TERRAIN DATA

Alexander James Grant

Naval Training Equipment Center
Orlando, Florida

July 1972

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Technical Report: NAVTRAEQUIPCEN IH-211

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(A reprint of a thesis originally submitted to the University of Florida)

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NAVAL TRAINING EQUIPMENT CENTER
ORLANDO, FLORIDA 32813

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13. ABSTRACT The objective of this research is to develop an objective evaluation method for determining the "goodness" of various data compression techniques applied to radar landmass simulation data, to validate the objective evaluation method by comparison with a subjective evaluation performed by experienced radar operators and to compare the objective evaluation with the currently used terrain RMS error criteria. This research consists of the computation of simulated radar shadow displays, the computation of various measures of "goodness" which are combined in a performance criteria, and the subjective evaluation of the simulated displays.

The objective evaluation method which is developed measures the "goodness" of the data compression techniques in terms of the usefulness of the simulated radar displays. The results obtained demonstrate the inadequacy of the terrain RMS error criteria and the degrading smoothing effect introduced by polynomial data compression. It is recommended that, prior to the implementation of any terrain data compression technique in a radar landmass simulator, it be evaluated in the manner proposed.

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FOREWORD

The development of a successful digital radar landmass simulation technique has been a continuing goal of the Naval Training Device Center (NAVTRADEVCEN) for many years. Through a continuing parade of government project engineers and contractors, slow but steady progress has been made to the realization of this goal. A number of projects are in process, both in the Navy and the Air Force, to produce navigation and weapon system trainers incorporating digital radar landmass simulation techniques based on the research performed and sponsored by NAVTRADEVCEN.

The conventional evaluation technique, i.e., having "experts" look at or fly the simulator and then provide an evaluation, is fraught with difficulties. The range and variety of comments and the diversity of views make any evaluation seem a function of gaussian distribution rather than a consensus of opinion.

Mr. Grant's thesis is a significant contribution to the solution of this problem. Mr. Grant has attacked the problem in an engineering fasnion and produced some objective criteria for evaluation. He has indicated additional areas for investigation.

The evaluation of terrain data compression techniques by the comparison of the simulated displays, as presented here, is a step forward in providing an analysis of their effectiveness with respect to maintaining the quality of the radar display. The automation of this comparison via the performance criterion removes the subjectivity from the evaluation. While the development of any performance criterion has always been somewhat subjective if not outright arbitrary the technique presented here of using a combination of user oriented display parameters in the performance criterion has merit.

In addition to the objective evaluation technique, the subjective evaluation method developed in this thesis is an effective procedure for evaluating the requirements for and the quality of simulated radar displays used for navigation.

M Fischer

M. FISCHER
Head, Computer Laboratory
Naval Training Device Center

Evaluation of Data Compression Techniques
for Radar Landmass Terrain Data

By

ALEXANDER JAMES GRANT

A THESIS PRESENTED TO THE GRADUATE COUNCIL OF
THE UNIVERSITY OF FLORIDA IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF ENGINEER

UNIVERSITY OF FLORIDA
1972

I- E

TO

The Radar Operators who will train on Digital Radar Landmass Simulators utilizing the technology hopefully furthered by this research.

ACKNOWLEDGMENTS

The research represented by this thesis constitutes a portion of the research carried on at the U. S. Naval Training Device Center under the in-house project 1743-05. The author wishes to extend his gratitude to Dr. H. H. Wolff, Technical Director of the Naval Training Device Center, and Mr. J. C. Wootton, Director of Research and Technology, for their encouragement to extend the in-house project into this thesis.

The author would like to thank Mr. M. Fischer and Mr. L. D. Healy for their contribution to the supervision of the project, Dr. F. J. Murray for stimulating discussions of the project, Mr. C. K. Brown for his assistance in solving some of the numerous software problems encountered, and Mr. R. J. Diddle and Mr. H. M. McKinney for the construction and maintenance of the special-purpose radar display hardware. His appreciation to Dr. B. L. Capehart and the Supervisory Committee, Dr. E. J. Muth, Dr. R. Harden and Mr. J. C. Wootton for their guidance in the preparation of this thesis.

Finally, the author would like to thank Commander Leroy Hawkins and Lieutenant Commander M. D. Walker whose contributions were crucial to the completion of this research.

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ABBREVIATIONS

NAVTRADEVCEN	-	U. S. NAVAL TRAINING DEVICE CENTER
DRLMS	-	Digital Radar Landmass Simulator
ft	-	Feet
NM	-	Nautical Mile
RMS	-	Root Mean Square
TOPOCOM	-	U. S. Army Topographic Command
PPI	-	Plan Position Indicator
RLMS	-	Radar Landmass Simulator
XDS	-	Xerox Data Systems, Inc.
DOP	-	Direct Output Processor
STE	-	Source Terrain Elevation

Abstract of Thesis Presented to the Graduate Council
of the University of Florida in Partial Fulfillment of the Requirements
for the Degree of Engineer

EVALUATION OF DATA COMPRESSION TECHNIQUES
FOR RADAR LANDMASS TERRAIN DATA

By

Alexander James Grant

June, 1972

Chairman: Dr. Barney L. Capehart
Major Department: Industrial and Systems Engineering

The objective of this research is to develop an objective evaluation method for determining the "goodness" of various data compression techniques applied to radar landmass simulation data, to validate the objective evaluation method by comparison with a subjective evaluation performed by experienced radar operators and to compare the objective evaluation with the currently used terrain RMS error criteria. This research consists of the computation of simulated radar shadow displays, the computation of various measures of "goodness" which are combined in a performance criteria, and the subjective evaluation of the simulated displays.

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CHAPTER I

INTRODUCTION

A Statement of the Problem

The U. S. Naval Training Device Center, NAVTRADEVCEN, is an agency within the Department of Defense. Its unique role is to research, develop and improve methods and devices used to train military personnel in the complete realm of tasks within their profession, including the use of the latest and most sophisticated military equipment.

An area of concern of current training device research and development is the training of radar operators. The Computer Laboratory of NAVTRADEVCEN is actively engaged in developing techniques for digital radar landmass simulation, hereafter called DRLMS. DRLMS is the simulation of the radar displays which would be seen on an airborne radar which is scanning the earth's surface for the purpose of navigation or target identification.

It is to be understood that DRLMS is the implementation of the radar landmass simulation task utilizing totally digital techniques with the exception of the radar display itself. To date, however, radar landmass simulation has been accomplished using only analog simulation techniques. A discussion of current radar landmass simulation technology and the state of the art of DRLMS is presented in Chapter II.

The simulation of the radar landmass displays as described in Chapter II requires two types of information concerning the simulated landmass. These are:

(1) reflectance

(2) terrain elevation.

Reflectance is that property of a target which is expressed as the fraction of power reflected when the radar beam is normal to the target's surface. A target is defined as anything, natural or manmade, which is illuminated by the radar beam and reflects it.

Terrain elevation is the information which describes the terrain height above sea level. This information must be available for each resolution element, the smallest distinguishable unit of the simulated radar display. The size of a typical DRLMS resolution element is 250 ft x 250 ft, while a typical geographical area, or problem area, utilized by a digital radar landmass simulator is 1250 NM x 1250 NM. The use of 250 ft x 250 ft as the size of a typical resolution element is related to the resolution capabilities of typical radar cathode ray tubes and the resolving capabilities of typical radars determined by their pulse width. Airborne radars currently used for navigation have resolving capabilities in the range of 100 ft to 600 ft.

It is shown in Chapter II that a problem area of 1250 NM x 1250 NM with a resolution of 250 ft x 250 ft consists of 9×10^8 resolution elements. The representation of terrain elevation for each resolu-

tion element constitutes a major data storage and readout problem when considered in the light of the required real-time access by the simulator. This data storage problem is lessened through the use of data compression techniques. While without data compression the simulated radar displays are expected to be as good as the actual displays, data compression will cause deterioration of the simulated radar displays.

A discussion of the generation of simulated radar displays using the reflectance and terrain elevation information is presented in Chapter II.

The evaluation of any simulation method which is used to train personnel in complex tasks is difficult and usually requires obtaining a statistically significant sampling of trainee performance. However, this is not feasible for complex devices which are in their developmental stages. Consequently, such evaluations are usually made in a subjective manner. The results obtained by subjective evaluations of simulation methods are usually affected greatly by the personality and experience of the evaluators. Since it is also inadvisable to build expensive hardware based upon an untested simulation technique, the development of an objective evaluation method to test the simulation techniques is extremely desirable. This is particularly true for the use of data compression techniques in digital radar landmass simulators.

The Goals of this Thesis

The primary goals of this thesis are to:

(1) Develop an objective evaluation method for deter-

mining the "goodness" of various data compression techniques applied to terrain elevation data.

(2) Validate the objective evaluation method by comparison with a subjective evaluation performed by experienced radar operators utilizing simulated radar displays.

(3) Compare the objective evaluation with the currently used terrain RMS error criterion as the measure of "goodness" of a data compression technique. The terrain RMS error criterion is simply the root-mean-square error which is determined by the analysis of the source elevation data (no data compression applied) and the reconstructed elevation data obtained after a process of data compression and decompression.

Scope of Research

The mapping of radar illuminated points on the earth's surface to an aircraft ground range radar screen is illustrated in Figure 1. The point P on the surface of the earth is characterized by Φ, R and a reflectance, where Φ is the angle of the radial radar sweep to the aircraft heading and R is the ground range distance between a point on the earth's

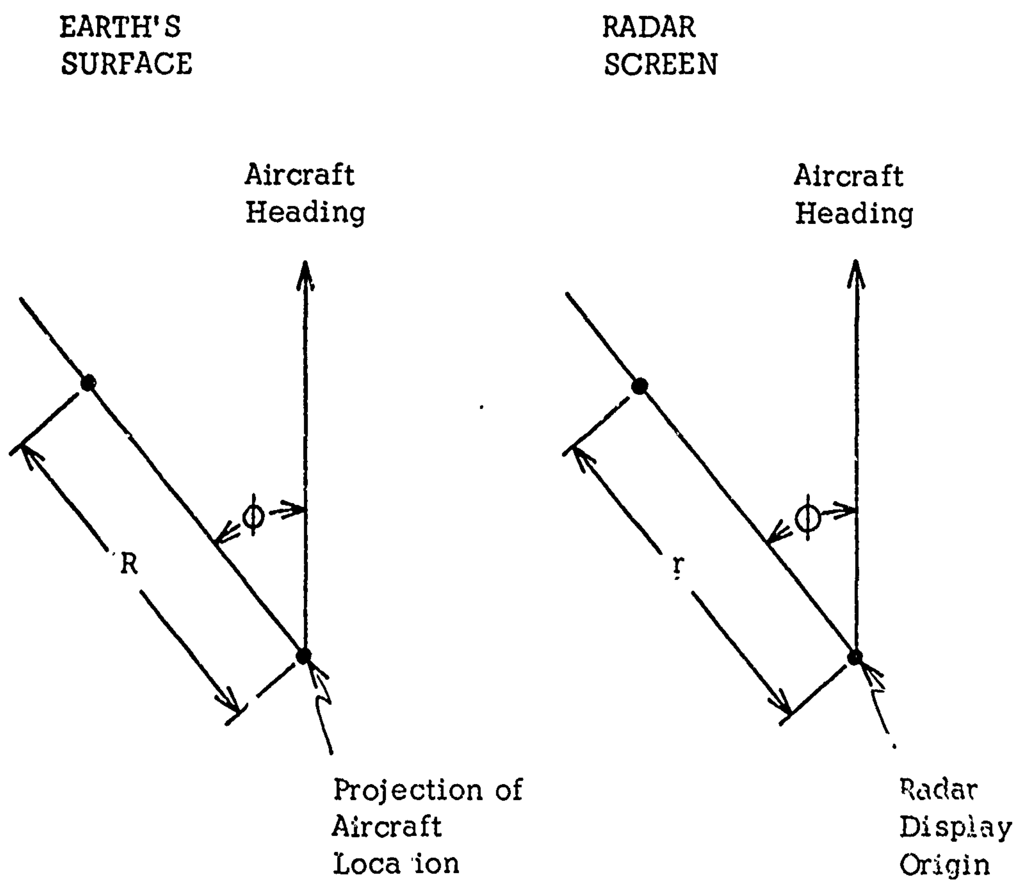


Figure 1

THE MAPPING OF THE EARTH'S SURFACE TO THE RADAR SCREEN

surface below the aircraft and point P. Once the earth curvature correction has been made, point P on the earth's surface maps into point p on the radar screen. Point p on the radar screen is characterized by ϕ, r and a brightness, where ϕ is the angle of the radial sweep to the aircraft heading and r is proportional to the range R. The brightness of point p is determined by the reflectance of P and the aspect angle between the incident radar beam and the normal to the earth's surface at point P. If point P is in radar shadow, however, the brightness of p is zero.

Radar shadowing occurs whenever the line of sight between the radar antenna and the point of interest on the terrain is obstructed by other terrain or "cultural targets," for example, manmade structures. An example of radar shadowing is shown in Figure 2. The area which is in radar shadow will be called a shadow and any area not in shadow will be called a nonshadow.

Whenever there are insufficient "cultural targets" such as cities, highways and railroads to be used for radar navigation, the navigator will rely on the terrain information on the radar display. The primary terrain information used for navigation is that of radar shadowing. In fact, it is not uncommon for a radar operator to turn up the gain on his radar receiver. This procedure eliminates shades of brightness and presents a display consisting of black and white areas representing shadow and nonshadow.

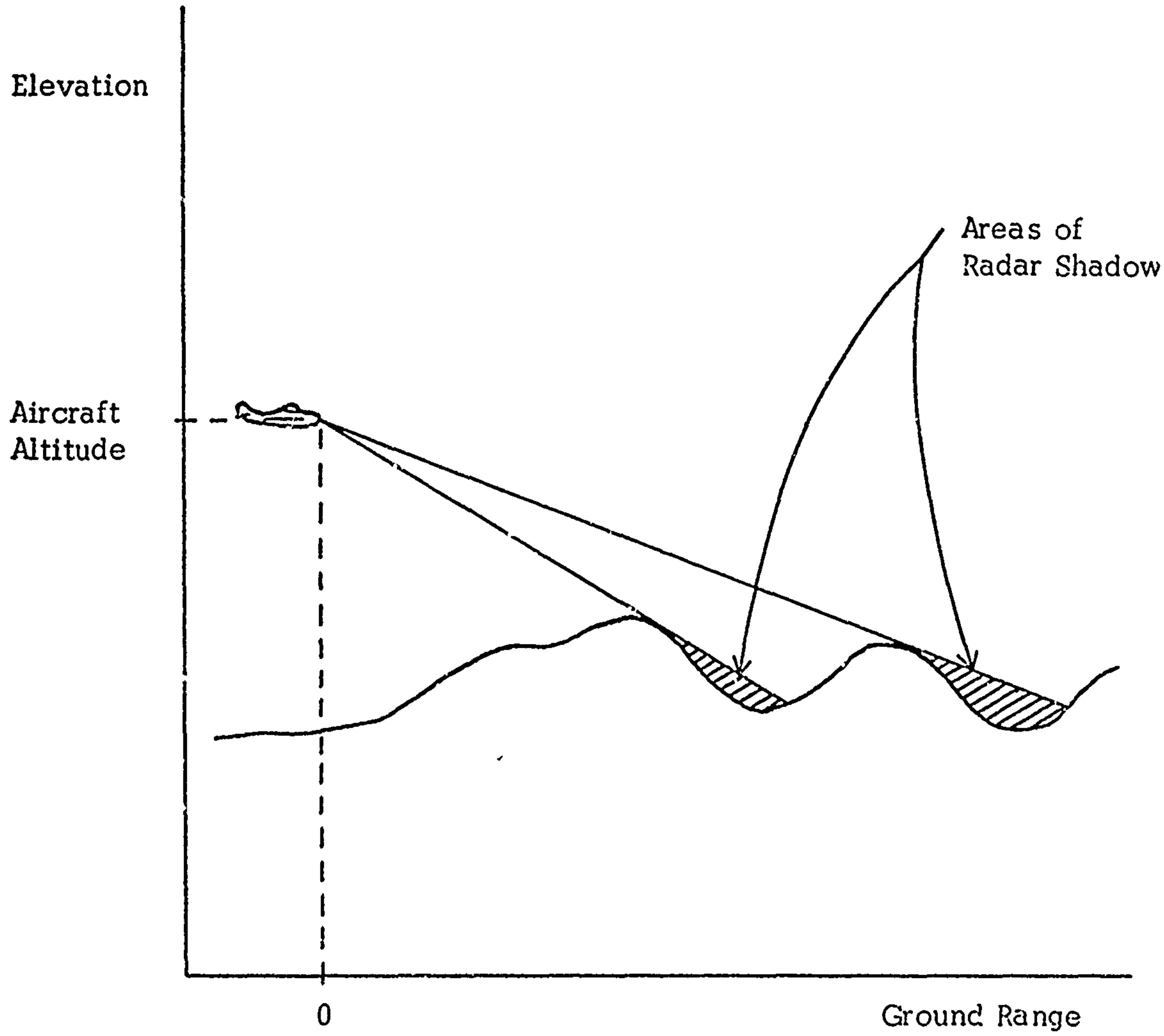


Figure 2

RADAR SHADOWS

Since it is normal for a radar operator to use only the shadow portion of the terrain information for navigation and since considering only that portion of the terrain data which produces radar shadowing reduces the complexity of the evaluation task, the author has so restricted this research. This restriction reduces the problem from a study of radar displays involving a continuous spectrum of shades of gray, a function of the reflectance and the radar beam angle of incidence, to a study of binary, that is black and white, radar displays.

In this research two data compression techniques were studied. The data compression techniques which were studied are a polynomial representation of the terrain elevation and a sampling method. These techniques are discussed in Chapter II and Chapter III.

Significant Contributions to Digital Radar Landmass Simulation

The research represented by this thesis has provided five significant contributions to digital radar landmass simulation. The five contributions are:

(1) The generation of nonreal-time radar shadow displays. Radar shadow displays were generated utilizing different data compression techniques as well as no data compression. This made possible, for the first time, a comparison of the radar displays generated

with different data compression techniques and radar displays generated without the use of data compression. The nonreal-time generation of radar shadow displays is presented in Chapter III.

(2) The terrain smoothing effects introduced by the use of the most highly touted polynomial data compression technique was demonstrated. The degradation of the simulated radar displays caused by this terrain smoothing is presented in Chapter IV.

(3) An objective method for evaluating terrain elevation data compression techniques was developed. This objective evaluation method consists of a performance criterion made up of four measures of "goodness." This objective method for evaluating terrain elevation data compression techniques is presented in Chapter IV.

(4) A systematic subjective method for evaluating simulated radar landmass displays

was developed. This subjective evaluation method is presented in Chapter V.

(5) The inability of the currently used terrain RMS error criterion to determine the usefulness of simulated radar displays utilizing terrain elevation data compression was demonstrated.

CHAPTER II

RADAR LANDMASS SIMULATION

Radar landmass simulation is the simulation of the radar displays seen on a radar scanning the earth's surface for the purpose of navigation or target identification. It is customary to think of landmass scanning radars, commonly called ground mapping radars, as airborne. On the other hand, shipboard radars which scan the shoreline are also considered as landmass scanning radars. All further discussion of radar landmass simulation is in the context of airborne radar since the shipboard radar can be considered a special case of the airborne, namely, that of an aircraft with a fixed altitude above the water.

Airborne ground mapping radars vary greatly depending upon the particular application and within each application. These variations are noted even for a particular radar set since any given radar set may utilize a variety of display formats, ranges, and resolutions. Examples of different applications for ground mapping radar are the radars used for terrain avoidance or terrain following, for target identification and for navigation.

The airborne radars which are used for navigation provide the aircraft's navigator with information of a gross nature about the terrain

elevation and target reflectance. Examples of this information are outlines of cities, hydrographic features, ridge lines, and shadows caused by intervening targets. The navigator uses these radar displays by comparing them with maps, target charts and radar predictions. A radar prediction is usually a hand sketched drawing made by the navigator of what he expects to see on his radar scope based on map and target chart data.

When flying a terrain avoidance or terrain following mission the navigator is very much concerned with the exact location of the hills and valleys, as well as the accurate determination of their elevations. In a similar manner, the use of radar for target identification requires considerable operator skill and a high degree of resolution of the radar equipment. In the target identification mode of operation the radar operator must locate on his radar display small targets at considerable distances, typically a building or a bridge many miles away from the aircraft.

A Concept of Radar Landmass Simulation

Prior to presenting any radar landmass simulation concept it is appropriate first to describe the process which is simulated as well as the simplifying assumptions. The physical process of radar scanning a landmass is depicted in Figure 3.

For many simulation applications the effects of atmospheric attenuation are considered to be negligible and are omitted. This is

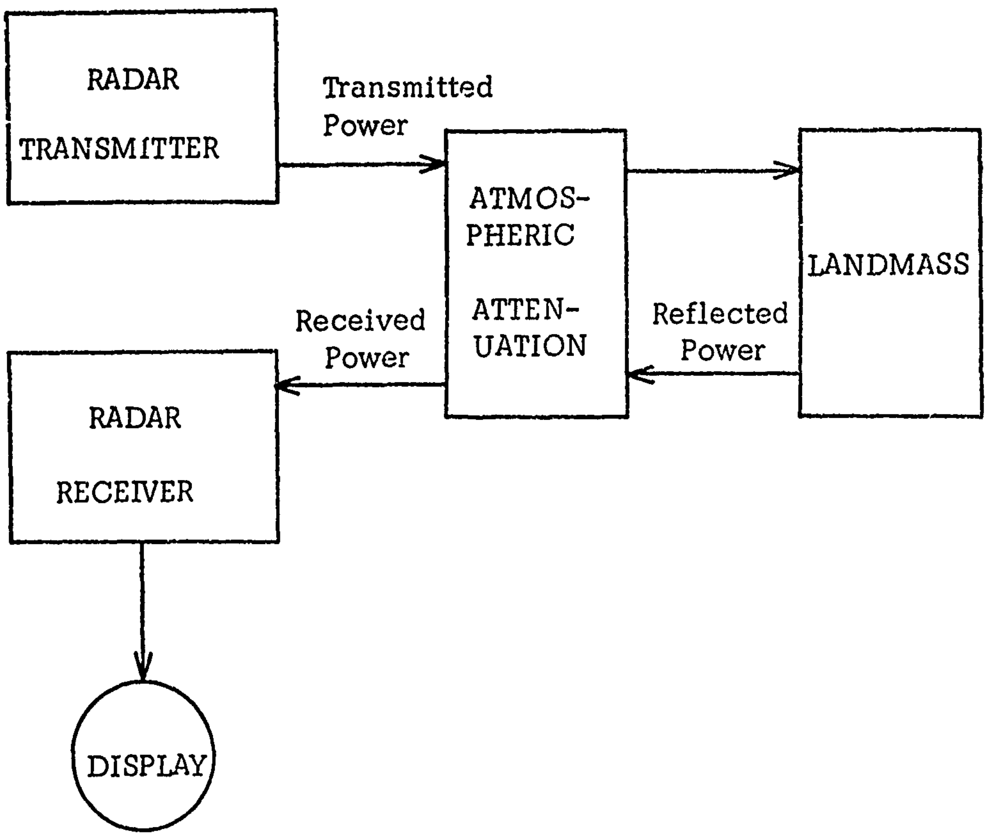


Figure 3

RADAR SCANNING A LANDMASS

particularly true for the less precise radars and for the use in the radar landmass simulations conducted for ideal weather conditions.

There are also some complexities of the actual physical process which are not apparent in Figure 3. For example, the effects of horizontal antenna patterns are either ignored in the simulation by assuming an ideal pencil-thin main lobe or are accounted for by a superposition of several ideal radar beams, one for each side lobe.

A basic radar landmass simulation, the first simplification of the actual process shown in Figure 3, is presented in Figure 4.

It is seen in Figure 4 that the simulation consists of four stages:

(1) Radar transmitter simulation

(2) Landmass reflection simulation

(3) Radar receiver simulation

(4) Radar display.

Radar Transmitter Simulation

Radar transmitter simulation provides the simulation of such parameters as the amount of transmitter power, vertical antenna pattern, antenna tilt, and others.

Landmass Reflection Simulation

The landmass reflection simulation simulates the landmass with respect to its radar power reflection characteristics. The primary function of the landmass reflection simulation is to determine the time

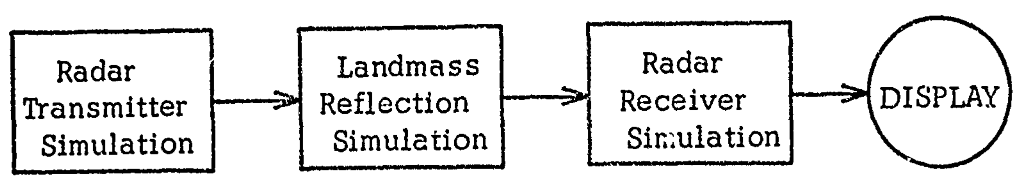


Figure 4

BASIC RADAR LANDMASS SIMULATION

dependent quantity of radar power that is returned to the radar receiver from the simulated landmass.

The two properties of the landmass which affect the amount of power returned to the radar receiver are the reflectance of the targets and their three-dimensional geometry with respect to the terrain and the aircraft.

The geometry that relates the targets and the aircraft is illustrated in Figure 5. The profile shown in Figure 5 is the view of a single radar sweep. A radar display consists of a sequence of radial sweeps. Some of the geometrical properties which affect the resultant display are:

(1) The slant range: the distance between the aircraft and the target, which can be determined from the ground range, aircraft altitude and terrain elevation as shown in Figure 5.

(2) Radar shadowing: the obscuring of targets on the ground from the line of sight of the radar which is caused by the intervention of other targets or terrain.

(3) The aspect angle effects: which are described by Lambert's Law which states that the ratio of returned power to incident power is proportional to the cosine of the angle between the incident radar beam and the normal to the surface.

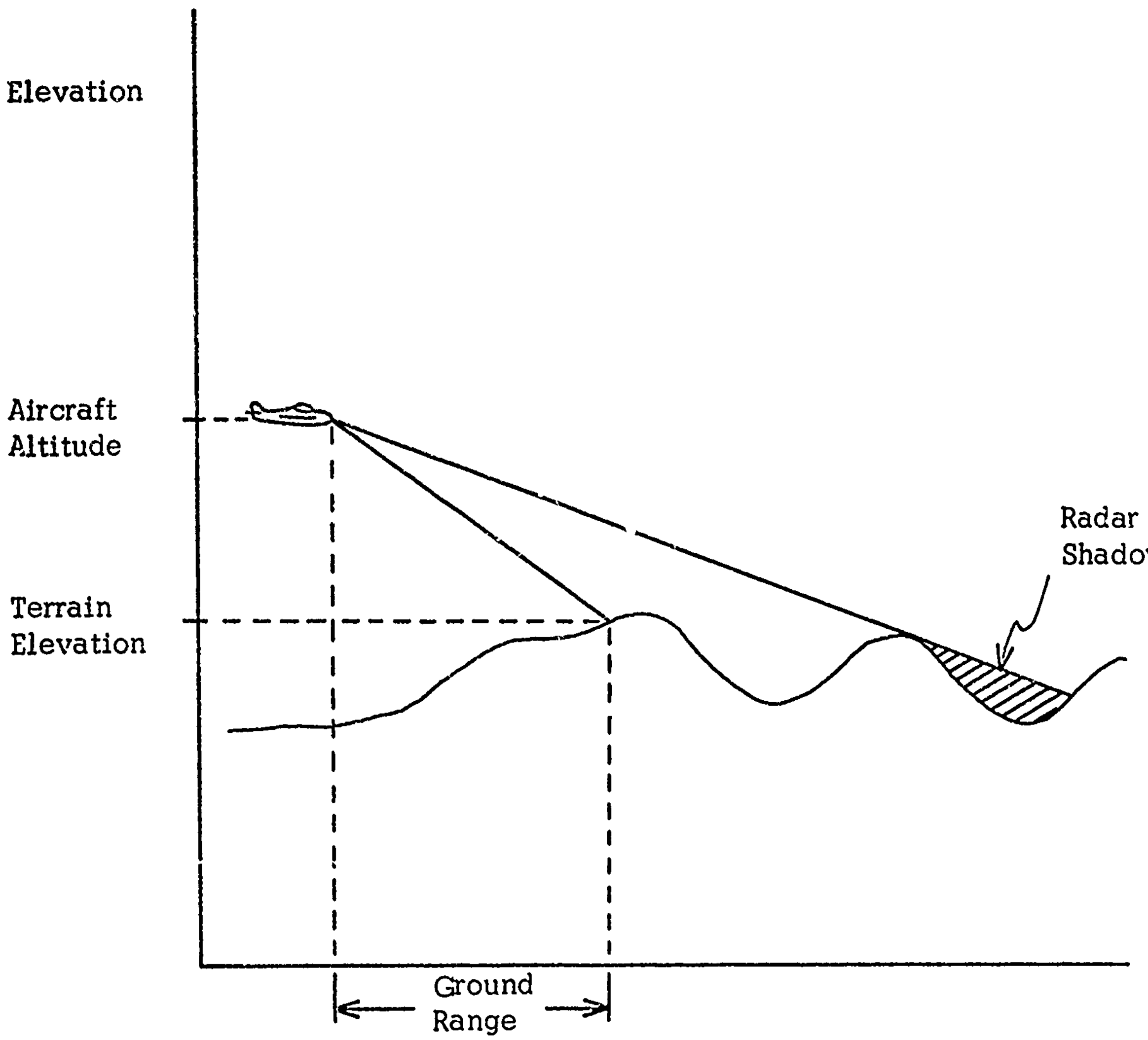


Figure 5

TERRAIN PROFILE

The variation of target reflectance along a radar sweep is depicted in Figure 6. The reflectance is that property of the target which is expressed as the fraction of power reflected when the radar beam is normal to the target's surface. Of the typical targets shown in Figure 6 it is noted that large cities have the highest reflectance and water has zero reflectance.

In the basic radar landmass simulation described in Figure 4 the effects of the above properties of the landmass and its geometrical relationship to the aircraft are combined in the landmass reflection simulation. The output of the landmass reflection simulation is the power of the return signal as a function of time.

Radar Receiver Simulation

Radar receiver simulation provides the simulation of such radar receiver parameters as receiver gain and video gain. The signal from the landmass reflection simulation is transformed in a manner prescribed by radar receiver simulation. The output of the radar receiver simulation is the signal to drive the radar display.

Radar Landmass Simulation Data Base

All radar landmass simulators must represent the terrain elevation and target reflectance information of an area of the real world. This information is called the simulator data base. The area represented by the simulator for one problem area in the currently used training devices is 1250 NM x 1250 NM or larger.

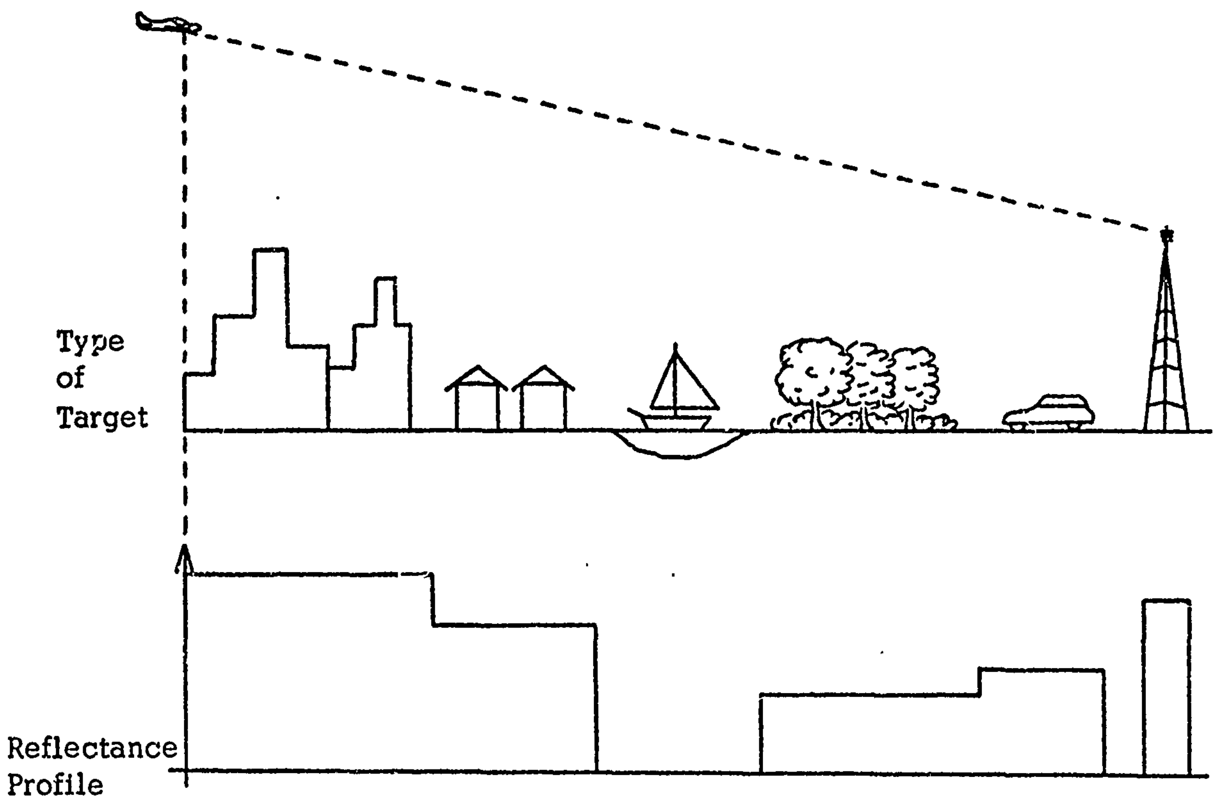


Figure 6

REFLECTANCE PROFILE

The lateral or horizontal resolution requirement for the data base of radar landmass simulators used for navigation training is typically 250 ft. This implies that the terrain elevation and reflectance information must be available for each resolution element, 250 ft x 250 ft area of the data base.

The number of resolution elements on a 1250 NM x 1250 NM data base is 9×10^8.

Current RLMS Technology

To date, radar landmass simulators have been analog devices. The most successful and those which are currently in use are transparency-type radar landmass simulators.

In the transparency-type simulators the data is stored on photographic transparencies. Data is extracted from the transparency by a flying spot scanner. Both the terrain elevation data and the reflectance data are coded as shades of "gray." The photo-optic information generated by the flying spot scanner is converted to electrical signals by photomultiplier tubes.

The signals generated by the photomultiplier tubes are processed by analog computation hardware. This processing uses the terrain elevation and reflectance data from the transparency as well as aircraft flight and radar set parameters to generate the simulated radar display.

There are two methods of transparency-type radar landmass simulation. They are: (1) a factored transparency system where there are two photographic transparencies with one transparency for the terrain elevation and the other for the reflectance data; and (2) a color system where each type of information is stored as a separate color on a single color transparency. The latter system must provide additional optics to separate the colors, while the former must provide alignment between the two flying spot scanners which read the two transparencies.

The radar data is stored on the photographic transparencies at a 3,000,000:1 reduction. Therefore, for the currently used 1250 NM x 1250 NM geographic problem area the photographic transparencies are two and one-half feet square.

Disadvantages of Transparency RLMS

For each of the transparency approaches to the radar landmass simulation task there exists a set of common problems. These problems are:

(1) High cost of the original photographic transparencies.

(2) High cost of duplicate transparencies for additional trainers.

(3) The inability to update existing transparencies; a remanufacture is required.

(4) The mechanical and optical complexities

of positioning and scanning the transparencies.

(5) The need for a separate transparency and scanning system for each cockpit where multiple-station trainers are required.

(6) Simulations requiring a resolution of better than 250 ft, such as for terrain avoidance training, are not possible utilizing the current transparency technology.

Literature Survey

A survey of the literature on digital radar landmass simulation uncovered relatively few publications. Almost all of the published literature are reports generated as part of Department of Defence sponsored research. The sparseness of publications on DRLMS is attributed to the almost exclusive use of radar landmass simulation by the military and the competitive protection afforded to the manufactures by not publishing.

The earliest work on DRLMS is described in [1]. This 1960 report summarized the analog radar landmass simulation techniques and presented the requirements for a digital solution to the radar landmass simulation problem. The storage requirements of DRLMS were presented by [2] in 1962.

The functional representation of terrain elevation data was presented by [3] in 1963. The function representation techniques were developed into the use of modified Lagrange polynomial by [6] in 1966. Further analysis of the modified Lagrange polynomial is found in [13]. A planar representation of the terrain elevation data is presented in [15].

Various proposed designs for digital radar landmass simulators are presented in [4], [5], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16] and [17].

Digital Radar Landmass Simulation

Digital radar landmass simulation, DRLMS, is the implementation and solution of the radar landmass simulation task using totally digital techniques with the exception of the radar display itself. This includes digital storage of the terrain elevation and reflectance data.

The digital approach to radar landmass simulation solves most of the problems associated with the use of transparencies. In particular, revisions to the data base can be performed under program control. More than one digital trainer can access the same digital memory and higher resolutions can be obtained simply by storing more data.

There are at present several different types of digital radar landmass simulators being designed. The major difference between the various methods lies in the form in which the radar data is being represented and not in the implementation of the formerly analog computational elements.

In each of the methods propc d to date by the simulation industry the digital computation as well as data storage and retrieval requires special purpose digital hardware. This requirement is caused directly by the amount of computation and data retrieval required to generate the simulated radar display. For example, a typical PPI radar display consists of approximately 1500 radial sweeps. Each radial sweep consists of 1000 display elements, and the scan rate of the display can be as high as 100 degrees per second. The resultant computation and retrieval rate is approximately 400,000 display elements per second.

A straightforward and natural approach to DRLMS is to subdivide the area of interest into squares, and for each square store a terrain elevation and reflectance value. The lateral resolution of this type of system is defined by the size of the squares. For a 1250 NM x 1250 NM data base with a resolution of 250 ft x 250 ft there are 9×10^8 resolution elements.

The size of the digital data base memory for a digital simulator utilizing this straightforward approach is defined as the number of bits required to store the terrain elevation and reflectance data for all 9×10^8 resolution elements. If the resolution of the reflectance and terrain elevation data is limited to 4 and 16 bits respectively, a resolution which equals or exceeds the current transparency systems, 20 bits of digital storage are required for each resolution element. The digital data base for a 1250 NM x 1250 NM area then consists of 1.8×10^{10} bits.

Data Compression Techniques

The storage of the 1.8×10^{10} bits required for the typical 1250 NM x 1250 NM area must be accessible for the real-time computation of the radar simulation. This constitutes a sizable and expensive high speed memory. This problem becomes even worse when additional requirements for better resolution or more coverage, that is, a larger data base, are added. It should be noted that the storage requirement increases inversely proportional to the square of the resolution. The resolution is defined as the size of the resolution elements. For example, a data base with a resolution of 125 ft requires 4 times the storage that is required by a data base with a resolution of 250 ft.

In general, the solution to the data storage problem is found by trading an increase in data processing for a decrease in the amount of data, that is, the use of some data compression scheme. These data compression techniques will cause deterioration of the simulated radar display.

There are many factors which affect the trading of computational effort for data storage and overall degradation of the resultant simulation. Some of these factors are the training requirements, the resolution, the amount of sophistication of the hardware, and the price.

Currently proposed data compression techniques for the radar landmass terrain elevation and reflectance data fall into one of three general categories. These categories are:

(1) Sampling methods

(2) Polynomial representations

(3) Planar surface fitting.

Sampling Methods

Sampling methods of data compression involve the selection of a single data value which will represent more than one resolution element. This selection may be fixed, random, or a result of some algorithm. Consider, for example, areas of 3 x 3 resolution elements. If each 3 x 3 area can be represented by one value, a net 9:1 data compression has been achieved. The selection of the one value which will represent the nine resolution elements involved may be fixed, for example, the value of the center resolution element for each 3 x 3 group; random, for example, the value for representative resolution element selected at random from the nine involved; or as a result of an algorithm, for example, an average or a maximum value. These sampling methods apply to both terrain elevation and target reflectance.

Polynomial Representations

Since the terrain elevation is essentially a continuous function, such as the terrain profile shown in Figure 5, the surface which describes the terrain can be approximated by a polynomial. Therefore, terrain elevation data compression utilizing polynomial representations can be applied to the terrain elevation data.

Since the reflectance data is typically discontinuous, as illustrated in Figure 6, target reflectance data does not lend itself to polynomial representations.

The polynomial-type data compression techniques all involve the use of a predetermined set of polynomial coefficients for each area, called a region. This set of coefficients is used to evaluate the prescribed polynomial to determine the terrain elevation, z, as a function of lateral variables, x and y, within the given region. If the number of bits required to represent the polynomial coefficients is less than the number of bits required to represent the data for each resolution element within the region, a net data compression will have been achieved. For example, coefficients are stored for each region of the data base. To determine the elevation of any point x_0, y_0 within any given region the polynomial is evaluated utilizing the stored coefficients for that region and the values x_0, y_0.

The net result of polynomial data compression is an approximation to the elevations of the terrain. The degree of accuracy of this approximation, the value of the root mean square error, is established at the time the coefficients are computed. The coefficients are computed once when the data base is first generated.

Planar Surface Fitting

The planar surface fitting techniques involve the approximation of the earth's surface by planes. The number of planes and the

shape of the polyhedral surfaces defined by the intersection of planes is determined by the accuracy required of the approximation, that is, the value of the root mean square error.

This, then, says the terrain elevation and reflectance data can be represented by the edges and vertices of these polyhedral surfaces. As long as the number of bits required to represent the edges is less than the number of bits required to represent the radar data for the resolution elements, a net data compression will have been achieved.

Evaluation of DRLMS Data Compression Techniques

In each of the above three data compression techniques the accuracy is defined by some error criterion, for example, the value of the root mean square error. While this is a mathematical measure of the accuracy of the technique it does not provide a measure of how the particular data compression affects the resultant simulated radar display.

The currently used error criterion for most data compression techniques is the root mean square error. With this situation it is possible to have achieved an overall root mean square error smaller than some desired value and have omitted from the approximated data base an important piece of information, a mountain peak, for example. While the root mean square error criterion has been satisfied the resultant radar display has a significant error.

These difficulties of relating the data compression techniques to the radar simulation are overcome in the objective evaluation procedure described in the following chapters.

CHAPTER III

THE GENERATION OF RADAR SHADOW DISPLAYS

As stated in Chapter I, the first goal of this thesis is to develop an objective evaluation method for determining the "goodness" of data compression techniques applied to terrain elevation data. The proposed evaluation method places an emphasis on the measurement of radar display parameters. This evaluation also requires a validation utilizing a subjective evaluation procedure by experienced radar operators.

Simulated radar shadow displays must first be created in order to perform either the objective or the subjective evaluation of terrain elevation data compression techniques. These displays must be computed utilizing each of the data compression techniques under evaluation and utilizing source terrain data with no data compression applied.

For the purpose of this research simulated radar shadow displays were generated in a 45° sector scan format, $\pm 22\frac{1}{2}^{\circ}$ about the aircraft heading. This sector scan format consists of a sequence of 90 radial sweeps $\frac{1}{2}^{\circ}$ apart, as shown in Figure 7. Each sweep consists of 576 display elements. Each display element is either black or white, corresponding to radar shadow and nonshadow respectively. Each display element represents 208.33 ft of ground range in the radial direction.

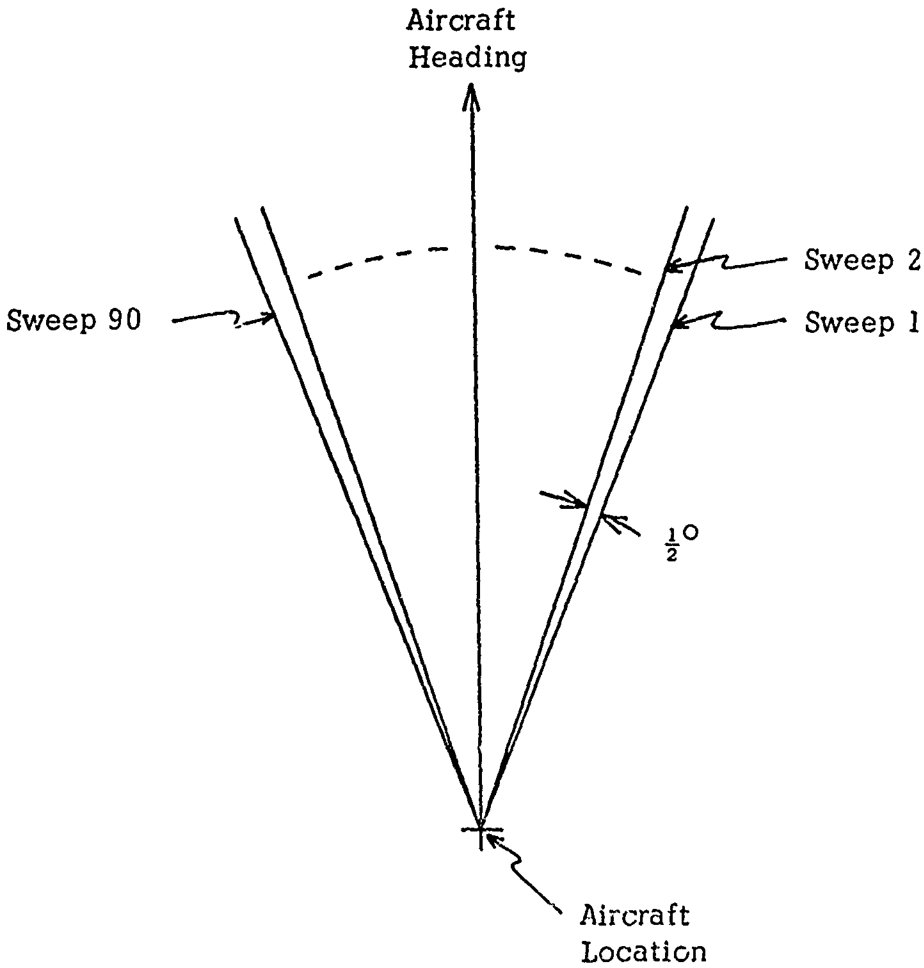


Figure 7

SIMULATED SECTOR SCAN

Therefore, the range of the radar, that is, the length of each sweep, is approximately 20 NM.

In order to obtain an evaluation for representative terrain the evaluations were performed utilizing several different geographical areas. For this study, four different geographical locations were used. These four locations, along with the aircraft heading which determines the display orientation with respect to a map, are given in Table 1.

Since the radar displays are a function of aircraft altitude the displays were generated for three altitudes at each geographical location. The three aircraft altitudes are 3500, 7000 and 20,000 feet.

The process of generating radar shadow displays is given in Figure 8. This process consists of four steps. These four steps are:

(1) Prepare data bases from the source terrain elevation data.-- One data base is prepared for each data compression technique to be studied. The generation of radar shadow displays in this research made use of five data bases. That is, the reference data base, the 625 ft, 1250 ft and 1875 ft data bases generated by the sampling technique, and the modified Lagrange polynomial data base.

(2) Generate terrain elevation profiles.-- A terrain elevation profile is the sequence of elevations along the simulated radar sweep.

TABLE 1

AIRCRAFT LOCATIONS USED FOR
SIMULATED RADAR SHADOW DISPLAYS

(1) Wilkes Barre, Pennsylvania

75° 75' West Longitude

41° 12' North Latitude

Aircraft Heading 45°

(2) Lock Haven, Pennsylvania

77° 23' West Longitude

41° 5' North Latitude

Aircraft Heading 315°

(3) Jersey Shore, Pennsylvania

77° 17' West Longitude

41° 6' North Latitude

Aircraft Heading 0°

(4) Coffin Rocks, Pennsylvania

77° 45' West Longitude

41° 15' North Latitude

Aircraft Heading 90°

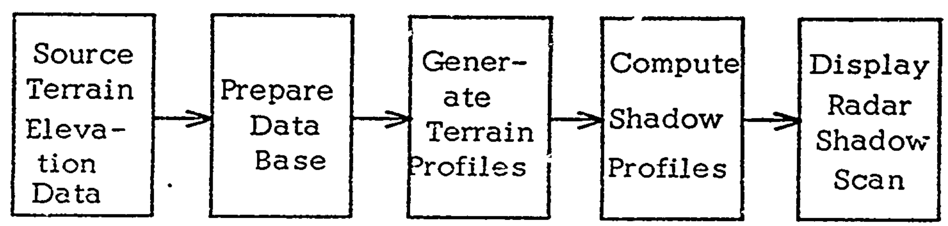


Figure 8

THE GENERATION OF RADAR SHADOW DISPLAYS

(3) Compute radar shadow profiles.--A radar shadow profile is the sequence of shadow and nonshadow data corresponding to the display elements of the simulated radar sweep.

(4) Display the radar shadow scan.

Each of these procedures and the source terrain elevation data are described in detail below.

Source Terrain Elevation Data

The original source terrain elevation data, STE, was obtained from the U. S. Army Topographic Command, TOPOCOM, Washington, D. C. The selected terrain data represents an area from 41° north latitude to 42° north latitude and 74° west longitude to 80° west longitude, approximately 71 NM x 276 NM. This area is described by U. S. Geological Survey maps NK 17-9, Warren, Pennsylvania; NK 18-7, Williamsport, Pennsylvania; and NK 18-8, Scranton, Pennsylvania.

The reference data base consists of terrain elevation values, to an integral number of feet, for a 208.33 ft square grid overlaying the 71 NM x 276 NM area described above. Each elevation value is the terrain height assigned to a 208.33 ft x 208.33 ft geographical area, a resolution element.

This reference data base is described as an n x m matrix:

$$M = \left[m_{i,j}\right] \tag{1}$$

Where $m_{i,j}$ = the elevation of the 208.33 ft x 208.33 ft resolution element at coordinates i,j.

The dimensions of this matrix n x m are 2072 x 7938, the number of resolution elements in each direction of the 71 NM x 276 NM geographical area.

The TOPOCOM terrain data was provided in the form of one magnetic tape file for each half of a Geological Survey map, each tape with its own coordinate system. To obtain a single unified digital data file for the area described above, the respective six map halves had to be fitted together. This process is called paneling. The paneling of the six map halves for the area of interest was performed by Pennsylvania Research Associates, Inc., under contract to NAVTRADEVCEN. This paneling process is described in [14]. Additional preprocessing was performed by NAVTRADEVCEN personnel to provide a uniform border of the digital terrain map, the digital terrain elevation data file, and to convert this digital terrain data into a form readable by the XDS Sigma 7 computer used for this research.

This STE data forms the reference data base. This reference data base was used to generate the standard radar shadow display, hereafter called the reference display.

Prepare Data Base

As indicated in Figure 8, the first step in the process of generating radar shadow displays is to prepare the data base. A data base

nomial. This technique and the polynomial coefficients for each 5000 ft x 5000 ft region of the geographical area described above are described in [14]. This modified Lagrange polynomial data base is also described below.

The Maximum Sample Data Bases

The generation of the 625 ft, 1250 ft and 1875 ft data bases made use of a maximum sample algorithm at three specified resolutions along with one stage of postprocessing. This procedure is shown in Figure 9. The data formats of the various magnetic tapes shown in Figure 9 are given in Appendix A. The input data to the maximum sample algorithm are the STE data, which is the reference data base.

The Maximum Sample Algorithm

The goal of the maximum sample algorithm is to determine one value of terrain elevation which will represent more than one basic resolution element. For example, a sampled data base with a lateral resolution of 625 ft can be derived from the 208.33 ft source data simply by partitioning the source data base into groups of 3 x 3 resolution elements and selecting one value which will represent each group of 9 resolution elements. The method of selection can be fixed, random, or algorithmic.

The philosophy of the maximum sample algorithm is simple. This method looks at the group of resolution elements which will be lumped together as shadow creators rather than possible shadows.

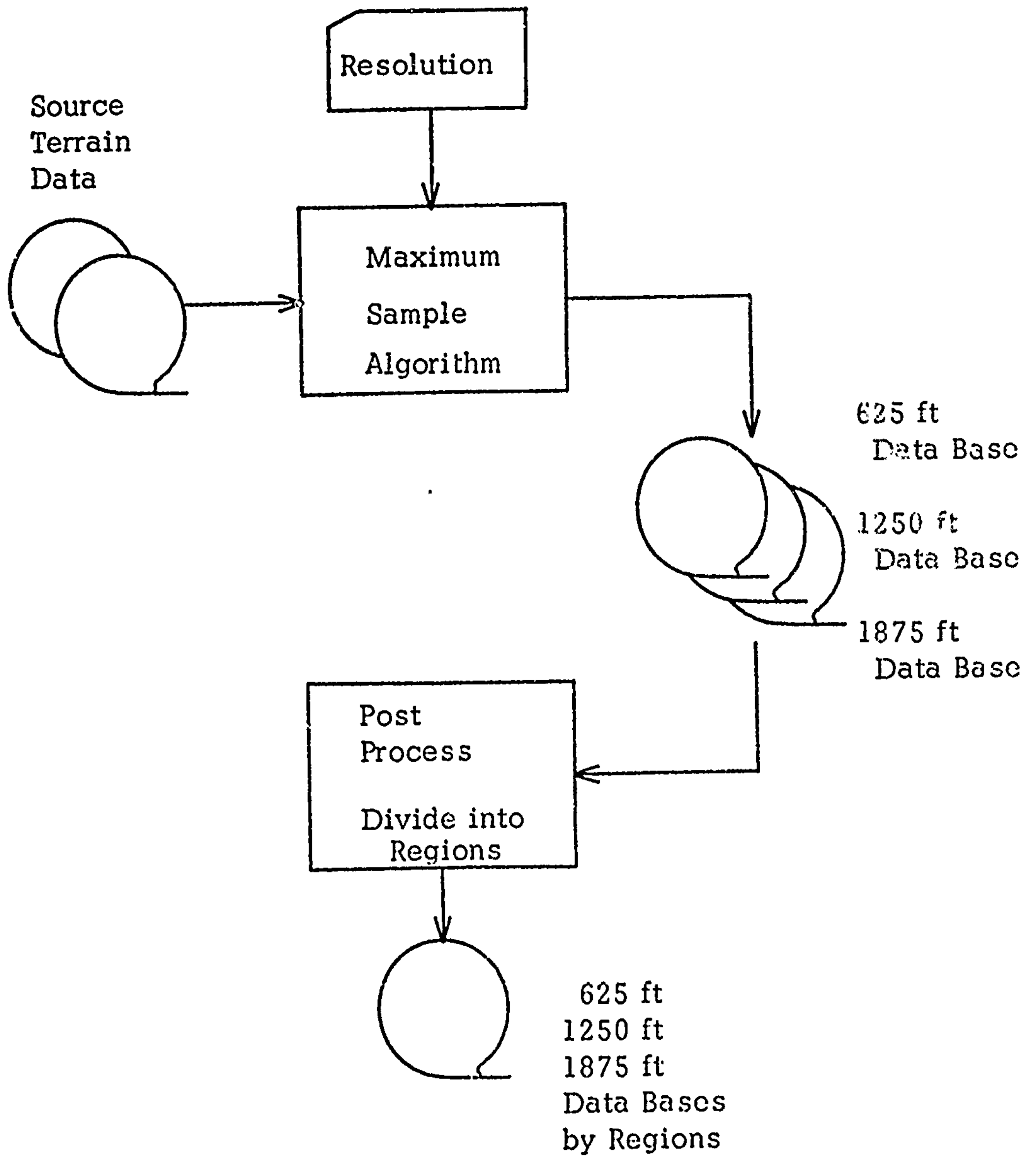


Figure 9

THE GENERATION OF THE 625 ft,
1250 ft AND 1875 ft DATA BASES

Therefore, when selecting the representative elevation from the group of resolution elements, the largest is selected.

This maximum sample algorithm is described by the equation:

$$n_{i,j} = \max_{k,l} \left\{ m_{k,l} \right\} \quad \begin{array}{l} k = N(i-1)+1, N(i-1)+2, \ldots, N(i-1)+N \\ l = N(j-1)+1, N(j-1)+2, \ldots, N(j-1)+N \end{array} \qquad (2)$$

Where $n_{i,j}$ = the resolution element i,j of the compressed data base.

$m_{k,l}$ = the resolution element k,l of the reference data base.

N = the number of reference data base resolution elements in the new compressed data base resolution.

The maximum sample algorithm used to generate the 625 ft, 1250 ft and 1875 ft data bases works as follows:

(1) Determine N, the number of source terrain elevation data base resolution elements in the new data base resolution. (Example - For a resolution of 625 ft N = 625 ft/208.33 ft = 3).

(2) Input a column of source data (the sequence of elevations in the south-north direction).

(3) Unpack source data (Note: Source data is packed 2 elevations per word).

(4) Find the maximum elevation for each group of N in the column of elevations.

(5) Save the column of maximum elevations.

(6) Repeat 2, 3, 4 and 5 a total of N times for successive columns.

(7) Find the maximum of the maximum elevations in the horizontal direction for the N saved maximum elevation columns.

(8) Output the column of maximum-maximum elevations.

(9) Repeat 2 thru 8 until the input data is exhausted.

This algorithm was exercised to obtain sampled data bases of 625 ft, 3 x 208.33 ft; 1250 ft, 6 x 208.33 ft; and 1875 ft, 9 x 208.33 ft. The resultant data compression is 9:1, 36:1 and 81:1 respectively.

Postprocessing - Divide the Maximum Sample Data Bases into Regions

In order to facilitate more efficient access by the subsequent software, the format of the data bases was changed from column, representing either 625 ft, 1250 ft or 1875 ft by approximately 71 NM, to regions consisting of 24 x 24 resolution units. Region identification numbers are assigned to each region to simplify subsequent software. These region identification numbers are assigned to the regions of the data bases from left to right and from bottom to top.

The Modified Lagrange Polynomial Data Base

The modified Lagrange polynomial terrain elevation data compression technique used in this research was developed in [6]. The development of this technique placed an emphasis on the ease in which the mathematics could be implemented in training device hardware. The progression of the development and application of this technique is described in [6], [7], [13] and [14].

When utilizing polynomial representations to provide data compression of terrain elevation data a set of polynomial coefficients

is stored for geographical areas, called regions. The size of a region for the modified Lagrange polynomial data compression technique is 5000 ft x 5000 ft. In order to determine the approximated elevation for any point in the geographical area represented by the data base one simply evaluates the prescribed polynomial using the coefficients for the region in which the point is located and the coordinates of the point as the independent variables.

For radar simulation it is necessary to reconstruct terrain profiles which cross region boundaries. It is desirable that the reconstructed terrain profiles make the transition across region boundaries in a smooth manner. That is, there should be no artificially generated bluffs or escarpments caused by errors in the polynomial approximation technique at the region boundaries. It is, therefore, advantageous to assure continuity of the polynomial approximation at the region boundaries. This desire for smooth transitions across region boundaries is extended to the slope of the reconstructed terrain profile as it crosses a region boundary. This will prevent artificially generated ridge lines or inflections.

With the proper selection of coefficients the modified Lagrange polynomial data compression technique assures boundary continuity of both the elevation profiles and their slopes.

The modified Lagrange polynomial which is a 5th degree polynomial representation for the terrain elevation is given in [13] as:

$$h_{X,Y}(x,y) = \sum_{i=0}^{5} \sum_{j=0}^{5} C_{X,Y,i,j}\, g_i(x) g_j(y) \tag{3}$$

Where X,Y = region designator

x,y = position in region

i,j = indices of summation

$C_{X,Y,i,j}$ = coefficients for region X,Y

$g_i(x)$, $g_j(y)$ = basis functions common to all regions

$$\left.\begin{aligned} g_0(Z) &= (1-Z)^3(1 + 3Z + 6Z^2) \\ g_1(Z) &= (1-Z)^3(1 + 3Z)Z \\ g_2(Z) &= (1-Z)^3 \tfrac{1}{2} Z^2 \end{aligned}\right\} \quad 0 \le Z \le 1$$

$$\left.\begin{aligned} g_i(-Z) &= (-1)^i g_i(Z) \\ g_{i+3}(Z) &= (-1)^i g_i(1-Z) \end{aligned}\right\} \quad \begin{aligned} &i = 0,1,2 \\ &0 \le Z \le 1 \end{aligned}$$

This polynomial representation has three properties which are advantageous when considered from the point of view of designing and constructing real-time radar landmass simulation hardware. These properties are:

(1) Superposition.-- The approximat terrain elevation at any point can be found by the superposition of several independently calculated functions. These calculations may be processed in a parallel manner with their results being summed to determine the resultant terrain elevation.

(2) Separability.-- Separability implies that the polynomial in two variables be separable into a product of two polynomials of one variable each.

(3) Tabulation of the basis functions.-- Since the basis functions, the separated independently calculated functions which are superposed, are the same for all regions, and since the simulation requires only elevations for integral values of the basic resolution element size, these functions need only be tabulated rather than evaluated.

The procedure by which the coefficients were found is given in [14], pp. 49-58. Basically the procedure was to compute the vector of $C_{i,j}$ which minimized the sum of the squares of the deviation errors, namely

$$\min_{C_{i,j}} \sum_{w} (Z(x_w, y_w) - h(x_w, y_w))^2 \qquad (4)$$

Where w - applies to all actual data points

$Z(x,y)$ - actual terrain elevations

$h(x,y)$ - reconstructed elevations using Equation (3) for the actual data points, w.

A complete Lagrange coefficient data base for the geographical area described above is available as a result of prior work sponsored by NAVTRADEVCEN. This data base consists of 36 coefficients per region. The region size is 5000 ft x 5000 ft. The data compression achieved by this method is approximately 64:1.

The reconstruction of the terrain elevation is accomplished by first computing and tabulating the basis functions. Then, for each point corresponding to the resolution elements of the reference data base within a region of interest, the approximated value of the terrain elevation, $h(x,y)$, is computed using Equation (3). This procedure was performed for all the regions associated with the radar displays generated in this research.

The Generation of Terrain Profiles

The generation of a terrain profile involves the extraction of the particular ter ain elevations which lie along the simulated radar sweep from the data base. Since the terrain elevation data is stored on a rectangular grid, a polar to rectangular coordinate transformation must be performed.

Since some of the data bases are quite large it became necessary to isolate the portion of the data base of interest, usually a group of regions forming a rectangular area, from the slow speed mass storage, namely the magnetic tape, and store that portion on random access disc. The portion of the data base which is loaded to random access disc con-

tains all of the terrain elevation data required to generate a radar display.

Terrain profiles were generated by the polar coordinate transformation and data point extraction algorithm. This algorithm determines the location of each display element along the simulated sweep. It retrieves the appropriate terrain elevation data, one region at a time, from random access disc and extracts from each region the required terrain elevation value.

Once the terrain profiles were generated by the polar coordinate transformation and data extraction algorithm they were stored in the digital file for the particular radar display. The structuring and maintenance of these terrain profile files was a major software task.

Loading Terrain Data Base Regions to Random Access Disc

The process of selecting the regions to be loaded to disc is illustrated in Figure 10. The representation of the data base in Figure 10 is divided into 28 regions, numbered from left to right and from bottom to top. To determine which of the data base regions to load to disc, one must first determine the location of the aircraft, the aircraft heading and the area of coverage for the radar scan. A 45° sector scan is illustrated in Figure 10. Since the loading of rectangular areas of data simplified the retrieval algorithm, regions 10, 11, 17 and 18 would be loaded to disc although the radar scan requires no data from region 17.

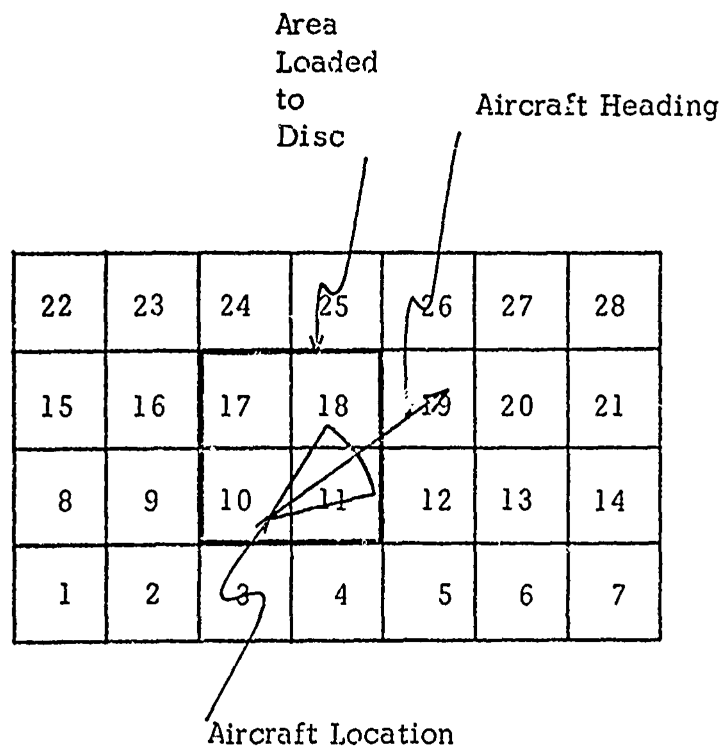


Figure 10

THE SELECTION OF THE DATA BASE REGION
TO BE LOADED TO DISC

The process of selecting which regions of terrain data to load to disc was accomplished manually while computing the terrain profiles for the maximum sample data bases, but it was automated into the terrain profile generation program for the source data and modified Lagrange polynomial data bases.

Polar Coordinate Transformation and Data Extraction Algorithm

The polar coordinate transformation and data point extraction algorithm uses the input parameters of:

(1) The number of data base regions in X-direction.
(2) The number of data base regions in Y-direction.
(3) The number of regions in X-direction loaded to disc.
(4) The number of regions in Y-direction loaded to disc.
(5) The location of the lower left corner of the portion of the data base on disc.
(6) The size of regions.
(7) The resolution of the data base.
(8) The aircraft location, heading and radar display format.

The above parameters are used to determine the storage address of each data point, a terrain elevation, of interest along the simulated radar sweep. The terrain elevation data is extracted from each of these storage addresses and the terrain elevation profile is assembled.

It should be noted that the polar coordinate transformation algorithm described below is an approximation. The location of data points are found to the greatest integer value less than or equal to exact

value. This approximation is justified in that the largest deviation from the exact sweep location is 208.33 ft for a sweep which is 20 NM long.

The polar coordinate transformation and data point extraction algorithm is logically defined as follows:

(1) Compute the X,Y position and a region identification number for each element along the sweep. The X,Y location of the jth element is given by:

$$X_j = \left[X_1 + j\cos\theta\right] \tag{5}$$

$$Y_j = \left[Y_1 + j\sin\theta\right] \tag{6}$$

Where X_1, Y_1 is the aircraft location.

θ is the sweep angle determined from the aircraft heading and the sweep number.

$[W]$ denotes the greatest integer value less than or equal to the argument W.

The region number of the jth element is given by:

$$R_j = \left[\left[Y_j/24\right] R_x\right] + \left[Y_j/24\right] + 1 \tag{7}$$

Where X_j, Y_j is the location of the jth element.

R_x is the number of regions in the X-direction of the data base.

There are 24 resolution elements per region.

(2) Extract the appropriate elevation value for each point, X_j, Y_j, along the sweep, addressing the contents of the region R_j with X_j, Y_j modulo 24, since there are 24 x 24 resolution elements in each region. The location of the appropriate region on disc is computed utilizing the parameters of the disc loading algorithm; the number of regions in X and Y of data base, the number of regions in X and Y loaded to disc and the region number of the lower left corner of the regions on disc.

Terrain Profile File Structure and Maintenance

The display format selected for this study is a 45° sector scan with a range of 20 NM consisting of 90 sweep lines, $\frac{1}{2}^{\circ}$ spacing. To achieve the resolution of 208.33 ft, there is a storage requirement of 576 words per sweep with one word per terrain elevation value. This is equivalent to a 51,840 word file per scan. Since 22 of these files were required for the study, a file structure and maintenance procedure was instituted. This structure and maintenance procedure is described in Appendix A.

The Generation of Shadow Profiles

With the terrain elevation profile generated, the geometrical relationships between each terrain profile and the aircraft can be determined. For the purpose of explanation it is assumed that terrain profiles are continuous and differentiable. As illustrated in Figure 11, a radar shadow begins when the angle between the normal to the surface of the terrain profile and the incident radar beam exceeds 90°. The shadow ends when the terrain elevation exceeds the projection of the line from the aircraft through the shadow starting point.

The algorithm derived from the above and used to compute a radar shadow profile from the discrete terrain elevation profile is as follows:

(1) Let $K = 2$ and let N be the number of display elements in a simulated sweep.

(2) For point K, along the terrain elevation profile, determine the slope, m_1, of the straight line drawn between the points K-1 and K+1.

(3) For point K, along the terrain elevation profile, determine the slope, m_2, of the straight line drawn between the aircraft and point K.

(4) If $m_2 > m_1$, a shadow begins, go to (5). If $m_2 \leq m_1$, $K = K+1$, for $K < N$, go to (2); otherwise stop.

(5) $K = K+1$, if $K = N$, STOP; otherwise $A_K = m_2KC$.

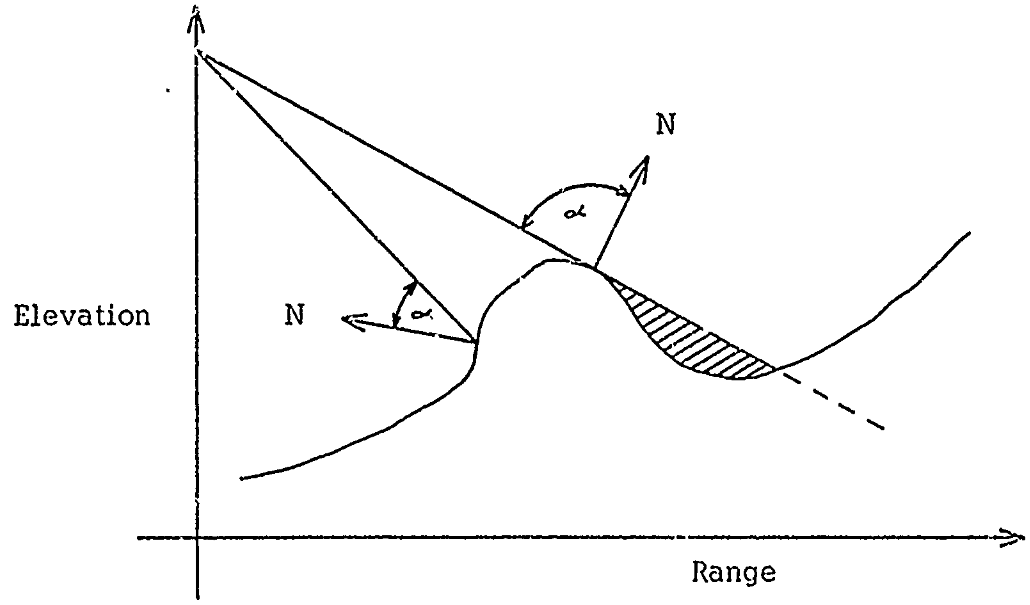


Figure 11

THE NORMAL TO THE SURFACE OF A TERRAIN PROFILE AND ITS RELATIONSHIP TO SHADOWING

Where C is the conversion from increments (resolution elements) to feet and A_K is the elevation of the projection of the line from the aircraft through the shadow starting point.

(6) If $H_K > A_K$; end shadow, go to (2); otherwise go to (5).

Where H_K is the elevation of the terrain at poing K.

This algorithm was exercised on each terrain elevation profile of a simulated radar display. A set of 90 shadow profiles was computed for each radar shadow display. Each set of shadow profiles is stored on magnetic tape as a single file.

Since sixty-two radar shadow displays were calculated in this study the data storage problem is several times more severe than was the case with the terrain profiles, where only twenty-two terrain files were calculated. This increase in the data storage requirement is a result of the computation of three shadow displays, one for each of three aircraft altitudes, at each geographical location of the aircraft. The terrain elevation is independent of aircraft altitude and thus requires only one data file while a radar shadow display is a function of aircraft altitude and thus requires a separate data file for the results of the computations at each aircraft altitude.

A file structure and maintenance system simular to that used for the storage of the terrain elevation data is used for the storage of

the radar shadow data. A description of this file structure and maintenance system is given in Appendix A.

Each set of shadow profiles constitutes a binary radar shadow display. This binary radar shadow display data is the input data to the subsequent evaluation software. One further step of processing is required to generate the visual radar shadow displays and their photographs. A discussion of this processing follows.

The Display of a Radar Shadow Scan

The last step in the process of generating radar shadow displays is the conversion of the radar shadow profiles into visual displays on a cathode ray tube and the resultant photographs. This final conversion was accomplished through the use of some special purpose input-output interface hardware and its software control.

The DRLMS Input-Output Interface

The DRLMS input-output interface unit was designed by the author as a special purpose input-output processor for the purpose of providing a real-time radar landmass simulation display capability for NAVTRADEVCEN. The DRLMS interface accepts control and data signals in two forms from the Sigma 7 computer used for this research. The first form consists of 96 discrete signal lines and the second form consists of 24 parallel data lines from the computer's Direct Output Processor, DOP. The DOP is a high transfer rate device with a data output capability of approximately one million bytes per second. The DRLMS inter-

face accepts deflection control and timing information from the discrete lines and it accepts radar display brightness information, data from the high speed Direct Output Processor.

The DRLMS interface generates the deflections for the CRT in the manner required for the radar sector scan through the solution of the following equations:

$$X_{n+1} = X_n + \Delta X \qquad (8)$$

$$n = 1, 2, \ldots\ldots, 575$$

$$Y_{n+1} = Y_n + \Delta Y \qquad (9)$$

The ΔX and ΔY discrete signals determine the slope of the sweep line. The most significant 11 bits of the 24-bit X and Y computations drive a digital-to-analog converter which in turn drives the deflection inputs of the Tektronic-type 602 display scope. The display scope has P7 phosphor, a typical radar phosphor.

For each increment, n, of the above equations the DRLMS interface provides the Z axis of the display scope with a corresponding brightness level. The interface obtains the video information from the Sigma 7 computer via the Direct Output Processor and holds it in a buffer memory until it is required, at which time it is supplied to the Z axis of the scope via a digital-to-analog converter. The interface has a capability of sixteen shades of gray, or brightness levels.

The initial positioning of each sweep is accomplished through the high speed interface, and the display timing is controlled via the discrete lines. For a more detailed description of this hardware, see [19] and [20].

Software to Generate Radar Shadow Displays

The software generating the radar shadow displays utilizing the DRLMS input-output interface can be separated into three routines.

(1) "REFORMAT," the routine which reformats the shadow profiles into the form required by the DRLMS interface.

(2) The High Speed Disc Handler, called "DISC."

(3) The display routine, "DISPLAY."

The routine "REFORMAT" reads the selected radar shadow display profiles from the shadow profile tape, and converts the binary data into the required intensity and "interface" buffer address format. This "interface" data list is then placed on the high-speed disc utilizing the "DISC" routine. This routine effects the high speed transfer of the data between the high-speed disc and core memory. "DISC" is written in assembly language. The data is transferred in a single 11,610 word (32 bits per word) block. The time required to effect such a transfer is typically less than 50 milliseconds.

The final program required in the generation of the visual radar shadow displays is that of "DISPLAY." This program performs the following tasks:

(1) Creates a data table of ΔX and ΔY values for each sweep of the display.

(2) Creates all the required input-output command and control words.

(3) Obtains the radar scan data from the high-speed disc using "DISC."

(4) Initializes each simulated radar sweep.

(5) Outputs control and timing for each sweep.

(6) Initiates the sweep and transfers the corresponding intensity, video, data.

Although this program is written primarily in Fortran, it makes use of an assembly code which is intermixed with the Fortran instructions. The assembly language code facilitates the execution of the special purpose input-output.

Several different radar shadow displays can be stored on the high-speed disc at one time. The selection of the desired scan can be made via data card when executing "DISPLAY." The radar shadow display appears on the display scope in a manner similar to a normal sector scan radar. The major differences are that the display contains only shadow-nonshadow information and the simulated aircraft is stationary. Photographs taken from the display scope are presented in Appendix B.

CHAPTER IV

THE OBJECTIVE ANALYSIS OF SIMULATED RADAR SHADOW DISPLAYS

The primary goal of this thesis is to develop an objective evaluation method for determining the "goodness" of various data compression techniques applied to radar landmass terrain elevation data. The term "goodness" of a terrain data compression scheme is defined as the quality of a resultant simulated radar display as it would relate to the effectiveness of training. An objective evaluation method utilizing this definition of "goodness" is presented below.

The objective evaluation method consists of a weighted sum of various measures of "goodness." This weighted sum is called the performance criterion. The contribution of each "goodness" measure to the overall performance criterion is a parameter which must be set as a function of the type of radar training desired. As presented in Chapter II, the differences in radar display requirements for navigation and terrain avoidance training are considerable.

Another goal of this thesis is to compare the objective evaluation method with the currently used terrain RMS error criterion. The major comparison is that of a mathematical error analysis upon a portion

of the simulation, namely that of the data compression technique, instead of its effect on the resultant simulated radar displays.

In order to compare the objective evaluation method with the terrain RMS error criterion it is necessary to compute the RMS error of the compressed-decompressed terrain elevation data for the same geographical areas used to generate the displays which are evaluated by the objective evaluation method. The terrain RMS error criterion and the terrain RMS errors for the four geographical areas used in this research are presented in this chapter.

Correlation techniques can be applied to the radar shadow displays generated with various types of data compression and those generated without data compression. These methods are not effective measures of "goodness" since they are primarily averaging techniques. The use of correlation techniques in the analysis of simulated radar displays lies in their ability to quantify translations or rotations of the simulated displays. The inability of correlation techniques to measure the "goodness" of resultant radar shadow displays and their effectiveness in determining translations or rotations of simulated radar displays are presented below.

Correlation Techniques

A Hypothesis

It was hypothesized that the use of correlation and correlation techniques would not provide a measure of "goodness" any better than

any other averaging method, the RMS error of the terrain elevations, for example. To substantiate this hypothesis, correlations were computed for several of the radar shadow displays. Autocorrelations and crosscorrelations were computed for radial sweeps and for range rings; arcs of constant radius from the aircraft defined by one resolution element from each of the simulated display sweeps.

The sequences of "0's" and "1's," that is, the shadows and nonshadows, which made up the radial sweeps or range rings were made periodic prior to performing any correlation by repeating the sequences. The autocorrelation of the periodic shadow function, F, is defined as:

$$A_i = \frac{1}{n}\sum_{j=1}^{n} F_j F_{j+i} \qquad i = 0,1,2,\ldots,n-1 \tag{10}$$

Where F_j = jth element of the shadow function.
n = the number of elements in one cycle of the shadow function.

The crosscorrelation of the periodic shadow functions, K and F, is defined as:

$$C_i = \frac{1}{n}\sum_{j=1}^{n} F_j K_{j+1} \qquad i = 0,1,2,\ldots,n-1 \tag{11}$$

Where F_j = jth element of the test shadow function.

K_{j+i} = the (j+i)th element of the reference shadow function.

n = the number of elements in one cycle of the shadow function.

The problems associated with these correlation techniques are illustrated in Figure 12. The two curves shown in Figure 12 are of (a) the autocorrelation for the Wilkes Barre, Pennsylvania area at an aircraft altitude of 7000 ft and (b) the crosscorrelation of the Lock Haven, Pennsylvania area with the Jersey Shore, Pennsylvania area, both for an aircraft altitude of 7000 ft. These correlations are performed for a range ring which is approximately 14 miles from the aircraft.

For the autocorrelation shown in Figure 12(a) the peak at the origin has a magnitude of 0.78, and the balance of the plot remains near 0.62. The variation between the peak and the minimum is a function of the distribution of "1's" and "0's," that is, the nonshadow and shadow. Other such autocorrelations show as little variation as 0.02 between the peak and the minimum. The crosscorrelation, shown in Figure 12(b), has a peak of 0.35 and a minimum of 0.17. The degree of correlation indicated in Figure 12(b) is a result of the similarity between the two different shadow displays brought about by the fact that there are only two values, "0" and "1," in the sequences which were correlated.

While it might be possible to determine some statistical properties of a given radar shadow display using these correlation techniques, their use in the quantitative measurement of "goodness" is not at all apparent. In fact, the unanswered question, what value of the

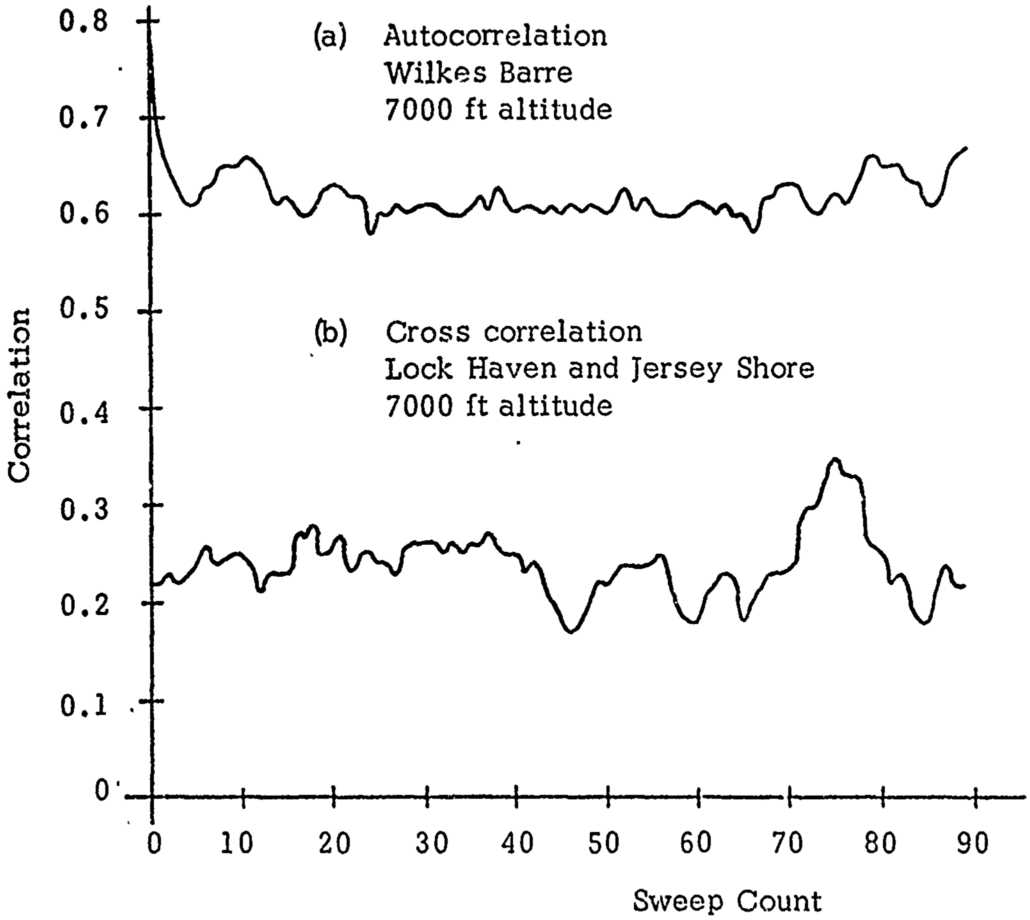


Figure 12

COMPARISON OF RADAR SHADOW DISPLAYS
USING CORRELATION TECHNIQUES

crosscorrelation function represents a measure of the radar display which will provide effective training, arises.

The Determination of Translations and Rotations

Although the use of correlation methods does not show much promise as measures of "goodness," they can be used effectively as an analytical tool for the evaluation of translations and rotations between a reference radar display and a test display.

The accurate determination of translations and rotations should be useful for the evaluation of radar landmass simulators with respect to:

(1) The positioning of the data base:
For navigation training the radar data displayed on the radar scope must be located accurately to provide coordinated simulation of both the navigation radar and the other navigation aids. Correlation techniques can be used as a measurement tool for data base positioning.

(2) The paneling of digital terrain maps:
The data bases of operational radar landmass simulators are a composite of many terrain maps which are paneled together.

Part of this paneling process requires the translation and rotation of the terrain data to account for the projections of the various maps. The correlation technique described below can be used to test the accuracy of the terrain map paneling.

To demonstrate the ability to detect a rotation, two radar shadow displays computed for the same aircraft position but slightly different headings were correlated. The two displays which were correlated are:

(1) Wilkes Barre, Pennsylvania
75° 57' West Longitude
41° 12' North Latitude
Aircraft Heading 45°
Aircraft Altitude 7000 ft
625 ft Data Base.

(2) Wilkes Barre, Pennsylvania
75° 57' West Longitude
41° 12' North Latitude
Aircraft Heading 30°
Aircraft Altitude 7000 ft
625 ft Data Base.

The autocorrelation for the 14 NM range ring of the normal shadow display with an aircraft heading 45° is shown in Figure 13(a). Figure 13(b) is the crosscorrelation of the normal display with the test display which was generated for an aircraft heading of 30°. The peak of the crosscorrelation curve of Figure 13(b) is shifted exactly 15°, the

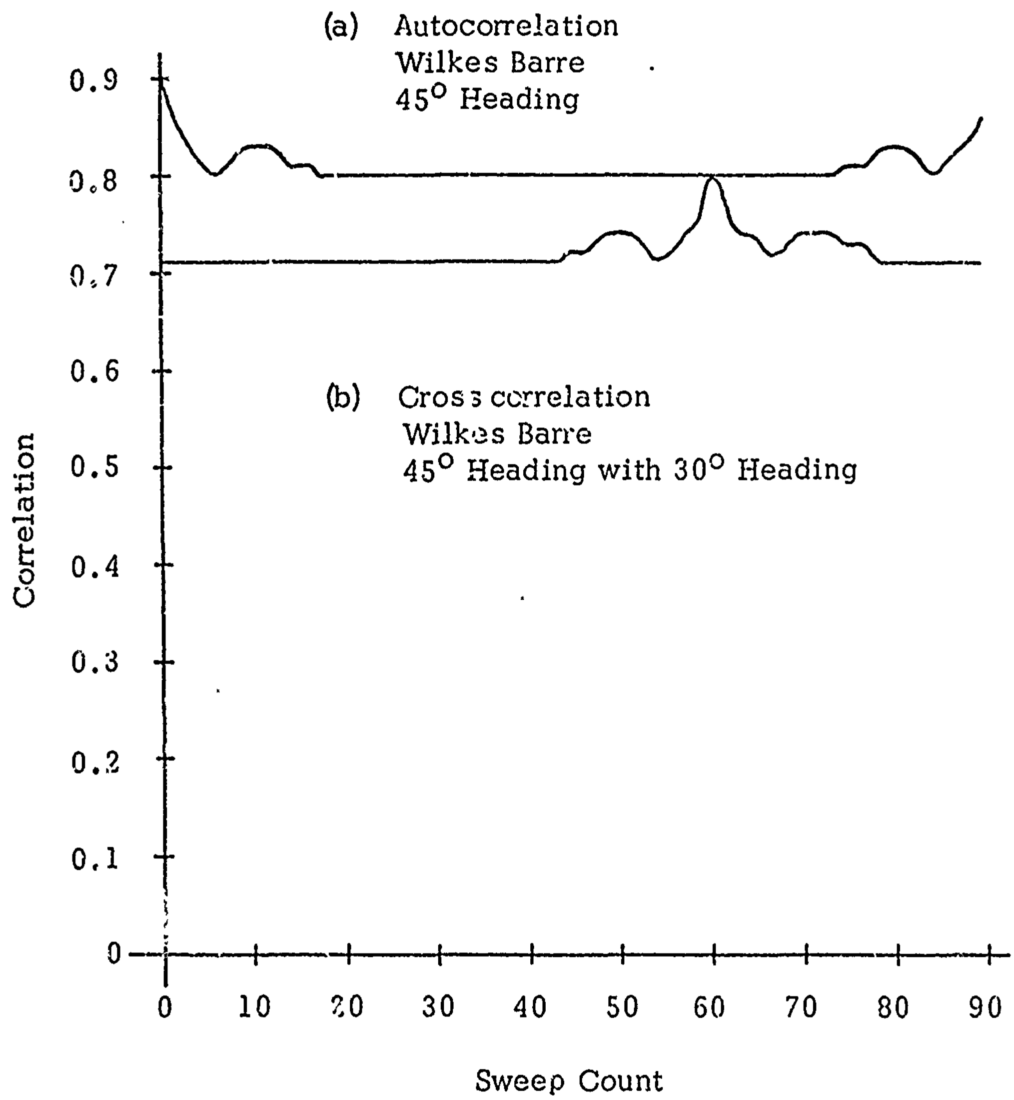


Figure 13

THE DETECTING OF DATA BASE ROTATION
VIA CORRELATION

precise rotation of the test display. This demonstrates the ability to quantify a rotation of a test display utilizing correlation methods.

To demonstrate the ability to detect a translation in a test display another radar shadow display was generated utilizing the 625 ft data base for the Wilkes Barre, Pennsylvania area with a heading of 45° and an aircraft altitude of 7000 ft. The one difference between this display and (1) above is that the aircraft is moved 7070 ft in a Northeast direction, along the aircraft heading. The autocorrelation of the normal display and the crosscorrelation of the normal display with the test display were made for various sweeps in the radar shadow display. A peak shift, corresponding to the 7070 ft translation, is clearly distinguishable for sweeps within ±15% of the heading of the translation. For sweeps greater than 15° from the heading of the translation a peak shift is indistinguishable. This demonstrates how a translation of a test radar display can be measured by the application of correlation techniques to the sweeps of the simulated radar displays. The determination of a translation is achieved by performing radial correlations through, at most, 180° of heading. The size of the sector in which a peak shift be measured is a function of the particular radar display, geographical area, and the amount of translation.

The RMS Error of the Terrain Profiles

The terrain RMS error criterion, as used in [14] for example, states that the "goodness" of a data compression technique is inversely

proportional to the RMS error of the reconstructed terrain. Since the number of terrain data points in the reference and test data bases are not the same the determination of the RMS error was made using the terrain profiles used to compute each display. Each terrain profile has the same number of terrain elevations, one for each display element. This RMS error is computed by the comparison of the terrain profiles generated from the reference data base and the terrain profiles generated from the compressed data base. This comparison is performed for each elevation along each terrain profile.

The RMS error is defined as:

$$E = \sqrt{\frac{1}{MN} \sum_{i=1}^{N} \sum_{j=1}^{M} (R_{i,j} - T_{i,j})^2} \tag{12}$$

Where $R_{i,j}$ = jth terrain elevation of the ith terrain profile for the reference display.

$T_{i,j}$ = jth terrain elevation of the ith terrain profile for the test display.

M = 576, the number of display elements per sweep.

N = 90, the number of sweeps per display.

A tabulation of the RMS errors for each geographical location versus data compression techniques is given in Table 2.

For each location the ordering by "goodness," from best to worst, is:

TABLE 2

THE RMS ERROR FOR TERRAIN PROFILES
(In feet)

AREA	DATA BASE			
	625 ft	1250 ft	1875 ft	Modified Lagrange Polynomial
Wilkes Barre, Pennsylvania	38.72	78.64	116.80	36.03
Lock Haven, Pennsylvania	103.51	203.63	292.06	73.67
Jersey Shore, Pennsylvania	104.58	213.47	328.88	79.39
Coffin Rocks, Pennsylvania	91.61	184.66	251.15	72.31

(1) Lagrange Polynomial

(2) 625 ft

(3) 1250 ft

(4) 1875 ft.

A comparison of this rating and that obtained via the objective evaluation given below and via the subjective evaluation is given in Chapter V.

Measures of "Goodness"

The proposed objective evaluation method endeavors to determine various "goodness" measure parameters of the simulated radar display and combine these measures into a single performance criterion in order to quantify the performance of the particular data compression technique under investigation. Four separate measures of "goodness" are determined for each test case radar shadow display, the radar display generated using the various compressed terrain elevation data bases.

Each of the four measures of "goodness" is one of two types; either an area measure or a connectedness measure. Each of the measures of "goodness" and the algorithms used to apply these measures to the radar shadow displays generated in this study is presented below.

Area Measures

In order to determine the "goodness" of radar shadow displays using area measures each of the display elements, which is either a shadow or nonshadow, is considered as a unit area that may contribute to three different area measures. These three measures are:

(1) Shadow Loss Measure

(2) Shadow Gain Measure

(3) Weighted Error Measure.

The Shadow Loss Measure

The shadow loss measure is merely the function of display elements of a test display which are not in shadow but should be. The value of the shadow loss measure is determined by comparing the test display with the reference display of the same geographical area and aircraft altitude on an element-by-element basis and counting the number of display elements in the test display which are nonshadow when the corresponding display elements in the reference display are shadow.

The shadow loss measure is defined by the author as:

$$L = \frac{1}{51,840} \sum_{i=1}^{90} \sum_{j=1}^{576} V_{i,j} \tag{13}$$

Where

$$V_{i,j} = \begin{cases} 1 \text{ if } R_{i,j} = 0 \text{ and } T_{i,j} = 1 \\ 0 \text{ otherwise} \end{cases}$$

$R_{i,j}$ = jth display element of the ith sweep of the reference shadow display.

$T_{i,j}$ = jth display element of the ith sweep of the test display.

The Shadow Gain Measure

The shadow gain measure is merely the function of display elements of a test display which are shadow but should be nonshadow. The value of the shadow gain measure is determined in the same manner as the determination of the shadow loss measure with the exception

that the number of test display elements which are shadow when the corresponding elements in the reference display are nonshadow are counted.

The shadow gain measure is defined by the author as:

$$G = \frac{1}{51,840} \sum_{i=1}^{90} \sum_{j=1}^{576} V_{i,j} \tag{14}$$

Where

$$V_{i,j} = \begin{cases} 1 & \text{if } R_{i,j} = 1 \text{ and } T_{i,j} = 0 \\ 0 & \text{otherwise} \end{cases}$$

$R_{i,j}$ = jth display element of the ith sweep of the reference shadow display.

$T_{i,j}$ = jth display element of the ith sweep of the test shadow display.

The Weighted Error Measure

It becomes apparent from discussions with experienced radar operators that errors in the radar display are not equally important for all parts of the display and for all aircraft altitudes. Because of the blooming, the very bright saturated display caused by the density of the sweeps in relation to the scope spot size, of the radar display near the center of the scope, very little importance is placed on this portion of the display. Also, very little importance is placed on a shadow display when flying at high altitudes. The term "high altitudes" is relative. For example, a 20,000 foot altitude when flying over the 2,000 foot high mountains of Pennsylvania is considered high altitude, but it is

not considered so when flying over the 16,000 foot high mountains of the Far East.

In order to bring this type of reasoning into a measure of "goodness" the following empirical function for weighting an error, either shadow that should have been nonshadow, or vice versa, in the jth element of the ith sweep was defined by the author as:

$$W_{i,j} = \tanh\left(\frac{j}{100}\right)\left(1 - \tanh \frac{A-H_{i,j}}{10,000}\right) \qquad (15)$$

Where j = range from the aircraft in display elements (20 NM = 576 elements)

i = sweep number

A = aircraft altitude

$H_{i,j}$ = elevation of the jth element of the ith terrain profile of the reference display.

The effect of the range and altitude dependent weighting factors is shown in Figure 14. The error weighting as a function of altitude is computed for aircraft altitude above the terrain, thus removing the relative definition of "high altitude" from the measure.

The overall weighted area measure, W, for a radar shadow display is then the sum of all the error weights with one error weight for each display element in error. The weighted area measure, W, for each test display in this study was normalized by dividing by 51,840, the number of display elements in the simulated radar display. It would

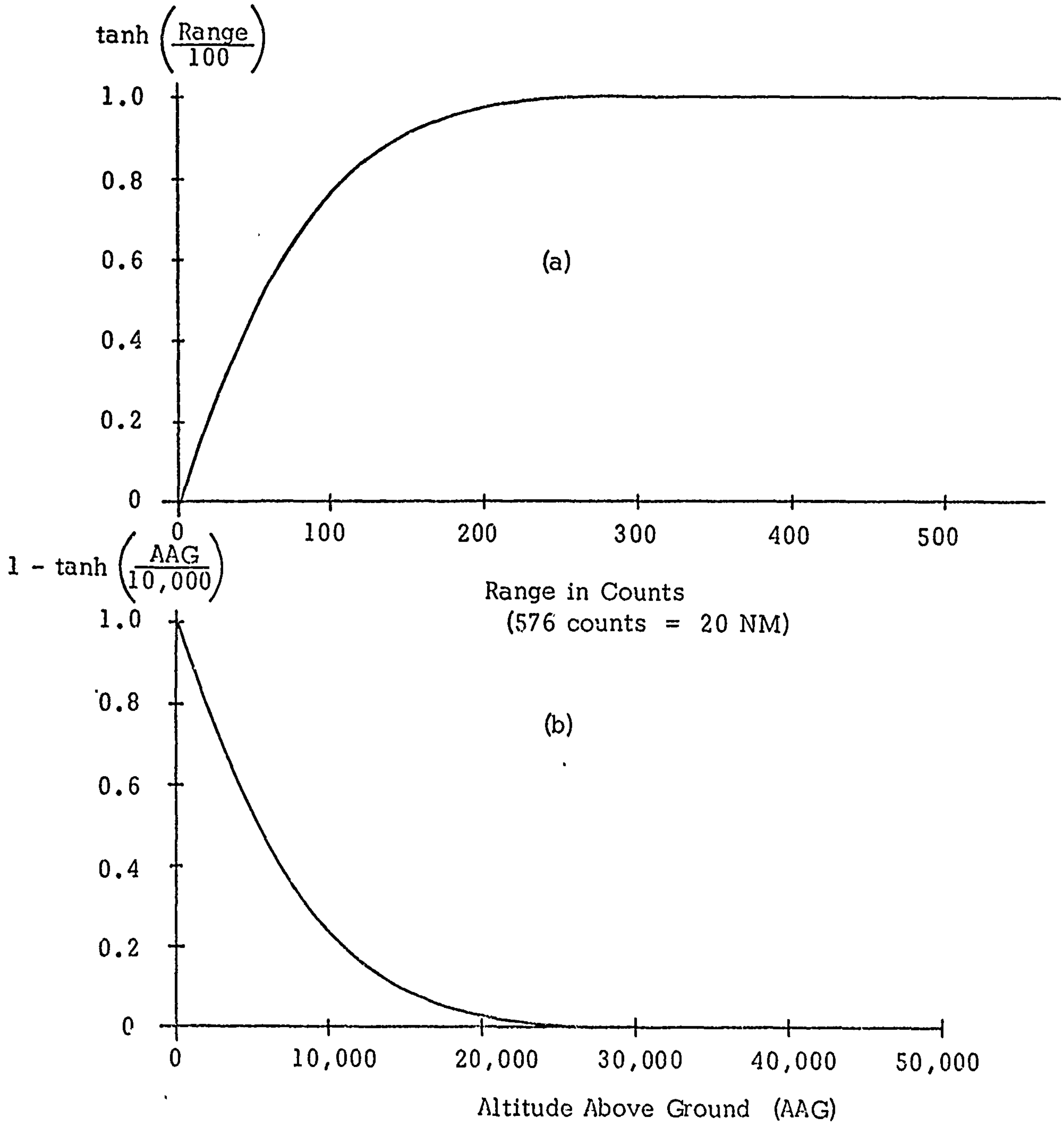


Figure 14

SHADOW ERROR WEIGHTING FUNCTIONS

be more correct to normalize W to the range 0 to 1 corresponding to no error to maximum error by dividing by the normalization factor:

$$n = \sum_{i=1}^{90} \sum_{j=1}^{576} \tanh\left(\frac{j}{100}\right)\left(1 - \tanh\left(\frac{A-H_{i,j}}{10,000}\right)\right) \tag{16}$$

Where A = aircraft altitude

$H_{i,j}$ = elevation of the jth element of the ith terrain profile of the reference display.

A single algorithm is used to determine all three area measures: the shadow loss, the shadow gain and the weighted error. This area measure algorithm is as follows:

(1) Initialize shadow loss, shadow gain, weighted error, j to 0. Compute the values of

$U_i = \tanh(R/100)$ for $R = i = 1,2,\ldots,576$.

(2) Add 1 to j.

(3) Read in the jth terrain elevation profile

$H_{j,i}$ $i = 1,2,\ldots,576$.

Where $H_{j,i}$ is the elevation of the ith element of the jth profile.

(4) Compute V_i.

$V_i = \tanh((A - H_{j,i})/10,000)$ for $i = 1,2,\ldots,576$.

Where A is the aircraft altitude.

(5) Read in the jth Reference Shadow Profile.

(6) Read in the jth Test Shadow Profile.

(7) $i = 1$.

(8) If the ith element of the Reference Shadow Profile is shadow, go to (10); otherwise, go to (9).

(9) If the ith element of the Test Shadow Profile is shadow, add 1 to shadow gain, add $U_i(1-V_i)$ to weighted error, and go to (11); otherwise, go to (11).

(10) If the ith element of the Test Shadow Profile is shadow, go to (11); otherwise, add 1 to shadow loss, add $U_i(1-V_i)$ to weighted error, and go to (11).

(11) Add 1 to i.

(12) If i = 577, go to (13); otherwise, go to (8).

(13) If j = 90, output shadow loss, shadow gain and weighted error; otherwise, go to (2).

The value for each of these area measures associated with each of the test cases; aircraft location, aircraft altitude, data compression technique, is given in Appendix B.

Connectedness Measures (A Measure of Terrain Smoothing)

Upon the comparison of the first radar shadow displays generated for the reference data base with the first radar shadow displays generated for the modified Lagrange polynomial data base it becomes quite apparent that the polynomial compression had degraded the displays. The shadow displays which were generated using the polynomial data compression had lost much of their fine structure, the smaller more detailed shapes. What was left were the major shadows giving a very

stylized appearance to the displays. Examples of the degradation introduced by the polynomial data compression are given in the case studies in Appendix B. This degradation was so striking and possibly misleading for navigation that it was concluded that it would adversely affect the usefulness of the polynomial compression technique in radar landmass simulators. Therefore, a measure of this property had to be determined such that it could be included in the overall performance criterion.

The polynomial data compression had smoothed the terrain, thus removing any of the small obstructions to the radar beam which would have created the smaller fine structure shadows. This terrain smoothing did not affect the general "average" terrain which produces the major shadows of the radar display. Since the reference displays have many more individual shadows and their larger shadows have complex structures, while the polynomial displays have fewer numbers of shadows with each shadow more simply connected, a measure to quantify the connectedness of the radar shadow displays was sought. Such a measure is generated by making use of some connectivity properties usually associated with pattern recognition.

This connectedness measure is defined by the author simply as a ratio proportional to shadow perimeter divided by shadow area.

The implementation of this connectedness measure requires the determination of (1) the perimeter and (2) the area of the shadows

for each radar shadow display. The types of display elements are defined:

(1) Inside border element: An inside border element is a shadow display element at a shadow-nonshadow interface.

(2) Outside border element: An outside border element is a nonshadow display element at a shadow-nonshadow interface.

(3) Interior element: An interior element is a shadow display element which does not form a part of a shadow-nonshadow interface.

The determination of shadow perimeter requires the identification and counting of inside and outside border elements. The perimeter of a shadow is approximated as one half the sum of its inside and outside border elements. The determination of shadow area requires the identification and counting of interior and inside border elements, the total number of shadow display elements in the display.

The identification of the border and interior elements of the radar shadow displays makes use of a definition which is derived in polar coordinates from the standard definition in rectangular coordinates

for Isolated, Border and Interior Elements of a digital picture, given in [21], pp. 133-134. The standard definition is:

> "Let S be a subset of a digital picture, and let $\overline{S}$ denote the complement of S (i.e., the set of picture elements not in S). The element (i,j) of S is called <u>isolated</u> if all its horizontal and vertical neighbors are in $\overline{S}$; i.e., if all of the elements, $(i - 1,j)$, $(i + 1,j)$, $(i,j - 1)$, and $(i,j + 1)$ are in $\overline{S}$. . . . Similarly, (i,j) is called <u>interior</u> if all of these neighbors are in S. If some of the neighbors are in S and some in $\overline{S}$, we call (i,j) a <u>border</u> element . . . ."

The polar coordinate definition for Isolated, Border and Interior Elements of a digital picture is as follows:

> Definition: Isolated, Border and Interior Elements of a digital picture.
>
> For a PPI type display with sweeps ϕ, and radial elements, ρ.
> Let S be a subset of a digital picture, and let $\overline{S}$ denote the complement of S (i.e., the set of picture elements not in S). The element (ϕ,ρ) of S is called <u>isolated</u> if all its coordinate neighbors are in $\overline{S}$; i.e., if all of the elements, $(\phi - 1,\rho)$, $(\phi + 1,\rho)$, $(\phi,\rho - 1)$, and $(\phi,\rho + 1)$ are in $\overline{S}$. . . . The element (ϕ,ρ) is called <u>interior</u> if all of these neighbors are in S. If some of the neighbors are in S and some in $\overline{S}$, we call (ϕ,ρ) a <u>border</u> element.
>
> One could also define alternative concepts using the four "diagonal neighbors" $(\phi - 1,\rho - 1)$, $(\phi - 1,\rho + 1)$, $(\phi + 1,\rho - 1)$, and $(\phi + 1,\rho + 1)$.

To determine if a display element is an interior element the subset S is defined as the shadow elements and the above definition is used to test for interior elements. To determine if a display element is an inside border element the subset S is defined as the shadow elements and the

definition is used to test for border elements. To determine if a display element is an outside border element the subset S is defined as the non-shadow elements and the definition is used to test for border elements. For the purpose of the connectedness measure the shadow elements which are isolated are considered as inside border elements.

The connectedness measure was implemented utilizing the above definition applied to each element of the radar shadow display and summing the number of display elements which were (1) inside border elements; i.e., border elements which were shadows, (2) outside border elements; i.e., nonshadow border elements, and (3) interior elements. Since it is possible to have shadows on the boundaries of the 45° sector scans used in this study, a nonshadow border was added around the scan.

The connectedness measure is defined empirically by the author as:

$$C = \left| 1 - \frac{(B_T + B_T')\ (I_R + B_R)}{(I_T + B_T)\ (B_R + B_R')} \right| \qquad (17)$$

Where B_T = the number of inside border elements of the test display

B_T' = the number of outside border elements of the test display

I_T = the number of interior elements of the test display

B_R = the number of inside border elements of the reference display

B_R' = the number of outside border elements of the reference display

I_R = the number of interior elements of the reference display.

When the ratios of perimeter to area of both the reference and test displays are the same which indicates no error C has a value of zero. As the ratio of perimeter to area for the test display decreases from the ideal given by the ratio of perimeter to area of the reference which indicates a more simply connected test display the value of C approaches unity. C will have the value of one when the test display becomes so simply connected that it disappears. The results obtained using this connectedness measure are presented in Appendix B.

The Performance Criterion

The overall objective of this study was to quantify the performance of various data compression techniques in terms of how "good" they are. We have defined various measures of "goodness," each measure aimed at quantifying a particular property of radar shadow displays which has utilized data compression as an intermediate step in its generation. The final step in the procedure to quantify performance is to combine all of the individual measures into one.

In order to allow the mixing of measures with different units it is required that each "goodness" measure be normalized. Each of the four measures of "goodness" defined above has a value of zero

when no error exists and has a value of one when the display is totally in error. Consequently, the four measures are normalized in the range 0 to 1.

The overall performance criterion defined by the author is:

$$P = \frac{K_1 W + K_2 C + K_3 L + K_4 G}{\sqrt{K_1^2 + K_2^2 + K_3^2 + K_4^2}} \tag{18}$$

Where W = the weighted area "goodness" measure

C = the connectedness "goodness" measure

L = the shadow loss "goodness" measure

G = the shadow gain "goodness" measure

K_1, K_2, K_3, K_4 = the coefficients determining the contribution of each "goodness" measure to the overall performance.

The value of P is zero for a perfect radar display, that is, a display with no loss in quality when compared to the reference display, and increases as the test radar display is degraded. The coefficients K_1, K_2, K_3 and K_4 determine the contribution of each "goodness" measure to the overall performance. The values selected for these coefficients are a function of the particular training application. The training application used for this study is basic navigation. Coefficients are selected such that the ranking of the four data compression techniques evaluated in this

study will correspond to the subjective evaluation presented in Chapter V. Based on the subjective evaluation the values selected for the K's are:

$$K_1 = 0.5$$

$$K_2 = 0.2$$

$$K_3 = 0.2$$

$$K_4 = 0.1$$

For these K values the performance of each data compression technique was computed for all twelve test cases; four geographical locations with three aircraft altitudes at each location. Figure 15 shows the overall performance of each data compression technique as a function of aircraft altitude averaged over the four geographical areas. The increase in the value of performance for the 1875 ft display at 20,000 ft is caused by a greatly increased contribution of the connectedness measure. This increase in the connectedness measure is attributed to the almost total loss of shadow information at this altitude for this data base.

Performance Criterion Sensitivity

If the performance criterion is to be useful as a tool to evaluate data compression techniques it must be stable. That is, the sensitivity of the performance criterion to small changes in any coefficient must not be so great as to change the ranking of the data compression

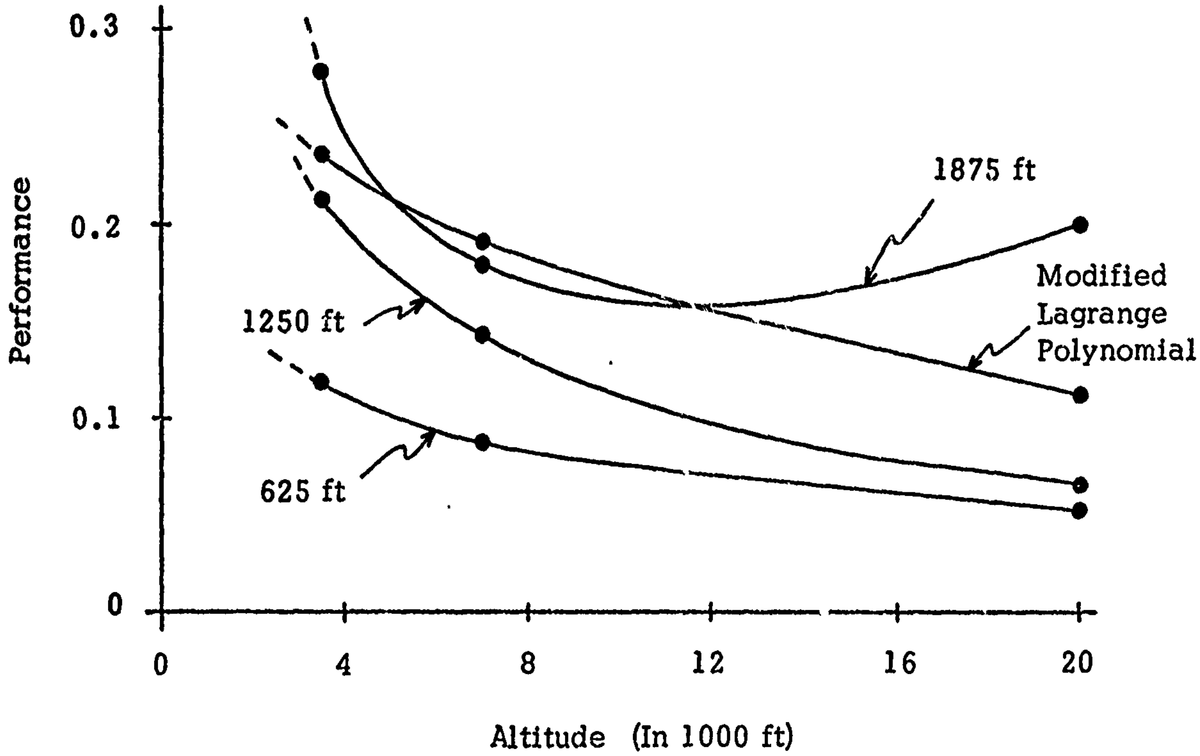


Figure 15

PERFORMANCE VS ALTITUDE

techniques being evaluated. A determination of sensitivity of the performance criterion to changes in individual coefficients is presented in Tables 3,4,5 and 6. The sensitivity analyses presented in Tables 3, 4, 5 and 6 are all for an aircraft altitude of 3500 ft. Similar analyses are performed for the other aircraft altitudes, 7000 ft and 20,000 ft.

The sensitivity of the performance criterion to changes in K_1, the contributor of the weighted area measure, is shown in Table 3. The performance of each data compression technique and its ranking is determined for the nominal coefficient values ($K_1 = 0.5$, $K_2 = 0.2$, $K_3 = 0.2$ and $K_4 = 0.1$) and for various values of K_1 above and below its nominal value while holding K_2, K_3 and K_4 constant at their nominal values. Similarly the sensitivity of the performance criterion to changes in K_2, K_3 and K_4 is shown in Tables 4, 5 and 6 respectively.

The range over which each coefficient can vary while holding the others constant without affecting the ranking of the data compression techniques was determined by examination of the sensitivity analysis tables. This range is given in Table 7.

The rate of change of the performance criterion for a change in a particular coefficient is given in Table 8. This rate of change is defined as the percent change in performance between its value for the nominal coefficients and its value for the maximum or minimum coefficients shown in Table 7 divided by the percent change in coefficient.

TABLE 3

K_1 SENSITIVITY ANALYSIS
(Aircraft Altitude 3500 ft)

K_1	0.2	0.3	0.4	0.5*	0.6	0.7	0.8	0.9
K_2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
K_3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
K_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
625 ft								
Performance	0.119	0.121	0.120	0.117	0.115	0.112	0.110	0.108
Rank	1	1	1	1	1	1	1	1
1250 ft								
Performance	0.215	0.218	0.215	0.211	0.206	0.201	0.197	0.193
Rank	2	2	2	2	2	2	2	3
1875 ft								
Performance	0.274	0.282	0.281	0.277	0.272	0.267	0.263	0.259
Rank	3	4	4	4	4	4	4	4
Lagrange								
Performance	0.279	0.265	0.248	0.233	0.222	0.210	0.201	0.193
Rank	4	3	3	3	3	3	3	2

*Nominal value of K_1

TABLE 4

K_2 SENSITIVITY ANALYSIS
(Aircraft Altitude 3500 ft)

K_1	0.5	0.5	0.5	0.5	0.5	0.5	0.5
K_2	0.1	0.15	0.2*	0.25	0.3	0.35	0.4
K_3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
K_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
625 ft							
Performance	0.117	0.118	0.117	0.117	0.115	0.113	0.111
Rank	1	1	1	1	1	1	1
1250 ft							
Performance	0.211	0.211	0.211	0.209	0.206	0.202	0.198
Rank	3	2	2	2	2	2	2
1875 ft							
Performance	0.285	0.282	0.277	0.271	0.264	0.256	0.247
Rank	4	4	4	4	4	3	3
Lagrange							
Performance	0.200	0.218	0.233	0.246	0.257	0.266	0.273
Rank	2	3	3	3	3	4	4

*Nominal value of K_2

TABLE 5

K_3 SENSITIVITY ANALYSIS
(Aircraft Altitude 3500 ft)

K_1	0.5	0.5	0.5	0.5	0.5	0.5	0.5
K_2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
K_3	0.0	0.1	0.2*	0.3	0.4	0.5	0.6
K_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
625 ft							
Performance	0.097	0.109	0.117	0.122	0.123	0.123	0.122
Rank	1	1	1	1	1	1	1
1250 ft							
Performance	0.168	0.193	0.211	0.221	0.227	0.228	0.227
Rank	2	2	2	2	2	2	3
1875 ft							
Performance	0.214	0.250	0.277	0.294	0.304	0.308	0.308
Rank	4	4	4	4	4	4	4
Lagrange							
Performance	0.206	0.224	0.233	0.236	0.235	0.230	0.224
Rank	3	3	3	3	3	3	2

*Nominal value of K_3

TABLE 6

K_4 SENSITIVITY ANALYSIS
(Aircraft Altitude 3500 ft)

K_1	0.5	0.5	0.5	0.5
K_2	0.2	0.2	0.2	0.2
K_3	0.2	0.2	0.2	0.2
K_4	0.0	0.1*	0.9	1.0
625 ft				
Performance	0.112	0.117	0.094	0.090
Rank	1	1	1	1
1250 ft				
Performance	0.205	0.211	0.154	0.147
Rank	2	2	2	2
1875 ft				
Performance	0.270	0.277	0.198	0.189
Rank	4	4	4	4
Lagrange				
Performance	0.229	0.233	0.161	0.153
Rank	3	3	3	3

*Nominal value of K_4

TABLE 7

COEFFICIENT RANGE FOR CONSTANT RANKING

Coefficient	Minimum Coefficient Value	Nominal Coefficient Value	Maximum Coefficient Value
K_1	0.3	0.5	0.9
K_2	0.1	0.2	0.35
K_3	0.0	0.2	0.6
K_4	0.0	0.1	above 1.0

TABLE 8

RATE OF CHANGE IN PERFORMANCE AS A
FUNCTION OF WEIGHTING COEFFICIENTS

Data Compression Technique	K_1 Decreasing	K_1 Increasing	K_2 Decreasing	K_2 Increasing	K_3 Decreasing	K_3 Increasing	K_4 Decreasing	K_4 Increasing
625 ft	-0.028	-0.085	0	-0.044	+0.171	+0.021	+0.043	-0.023
1250 ft	-0.032	-0.106	0	-0.057	+0.204	+0.038	+0.028	-0.030
1875 ft	+0.018	-0.193	-0.058	-0.101	+0.230	+0.056	+0.025	-0.032
Modified Lagrange	-0.330	-0.215	+0.282	+0.188	+0.116	-0.020	+0.017	-0.034

The rate of change is computed for both a change from nominal coefficients to minimum coefficients and to maximum coefficients.

The results shown in Tables 7 and 8 indicate that the performance criterion is stable. In fact, the stability with respect to K_4, the contribution of the shadow gain measure, is so great that the measure can be removed from the performance criterion without affecting its ability to rank the data compression technique . The cause of this insensitivity to changes in K_4 is the extremely small values of the shadow gain measure for all data compression techniques, as seen in the case studies of Appendix B.

The performance criterion is most sensitive to changes in K_2, the contribution of the connectedness measure. This sensitivity, as shown in the case studies of Appendix B, is a result of connectedness being a major component in the performance for the modified Lagrange polynomial displays and a minor component of the performance for the other techniques. Since the contribution of connectedness is very small for the 625 ft, 1250 ft and 1875 ft displays and large for the modified Lagrange displays, variations in K_2 have very little effect on the performance of the 625 ft, 1250 ft and 1875 ft displays while they have a large effect on the performance of the modified Lagrange displays, as shown in Table 4. Even though the performance criterion is most sensitive to change in K_2, it is still quite stable since it requires at least

a 50% change in the value of K_2 to change the ranking of the data compression techniques.

This sensitivity analysis has proven the performance criterion stable with respect to change in its coefficients; the contributions of each "goodness" measure to the overall performance. This stability allows considerable latitude in the selection of the weighting coefficients such that the ranking of the data compression techniques by the performance criterion is relatively independent of the subjective decision of how much of each "goodness" measure should be included in overall performance measurements.

CHAPTER V

SUBJECTIVE AND OBJECTIVE EVALUATIONS

The first goal of this thesis is to develop an objective evaluation method for determining the "goodness" of data compression techniques applied to radar landmass terrain elevation data. This objective evaluation method was presented in Chapter IV. The second goal of this thesis is to validate the objective evaluation method with a subjective evaluation. This subjective evaluation is presented below. The final goal of this thesis is to compare the results obtained by the objective evaluation method with the currently used terrain RMS error criterion discussed in Chapter IV. A comparison of the results obtained using the objective evaluation method, the subjective evaluation and the terrain RMS error criterion is given at the end of this chapter.

The Subjective Evaluation

The subjective evaluation of the simulated radar shadow displays consists of three tasks. These three tasks are:

(1) The performance task.

(2) The comparison.

(3) The rating.

The Performance Task

In order to provide a systematic approach to the subjective evaluation, experienced radar operators were requested to define which information in a radar shadow display they would use for navigation. When navigating using the terrain information of a radar display the experienced radar operator looks for recognizable features or any outstanding patterns. This amounts to looking for special shapes. The radar operators, as part of typical preflight preparations, prepare hand-drawn sketches called predictions of what they expect to see on their radar scope at various check-points in their mission. These predictions are prepared using the various maps and charts of the area of interest. Since the hand sketching of predictions is routine for the experienced radar operator, the information requested in order to define which information in a radar shadow display they would use for navigation was supplied as such hand-sketched predictions.

Hand-sketched predictions were obtained from two experienced radar operators. In order to reduce work to a reasonable level, each operator sketched only one prediction for each geographical area. These predictions were for an aircraft altitude of 3500 ft. Not preparing the predictions for other aircraft altitudes is further justified by the fact that the shadow structure for each altitude is basically the same with only the size of the shadows decreasing for increasing altitude.

To simplify the comparison of these radar display predictions with the computer generated plots, the radar operators prepared their sketches to the scale of the Geological Survey maps of the areas of interest. The scale of the maps used is 250,000 to 1. Consequently, a hand-drawn sketch of the 45° sector scan with a 20 NM range becomes a sector with a radius of approximately six inches.

A typical radar display prediction is shown in Figure 16. The area shown in Figure 16 is that of Coffin Rocks, Pennsylvania.

The Comparison

In order to measure the "goodness" of the various radar shadow displays on a subjective basis, it was necessary to compare each computer generated plot of the radar shadow display with the hand-sketched prediction for the particular geographical area of interest.

The first step in the comparison of the computer plot and the hand-sketched prediction was to enumerate the radar significant features on the hand-sketched prediction. Figure 17 shows the significant features of Figure 16 enumerated. This enumeration is performed for all geographical areas.

Using copies of the hand-sketched prediction, an overlay comparison using a tracing table was made for each computer plotted radar shadow display. A typical computer plot of a radar shadow display is shown in Figure 18. The plot shown in Figure 18 is for the Coffin Rocks, Pennsylvania area using the 625 ft data base. With the

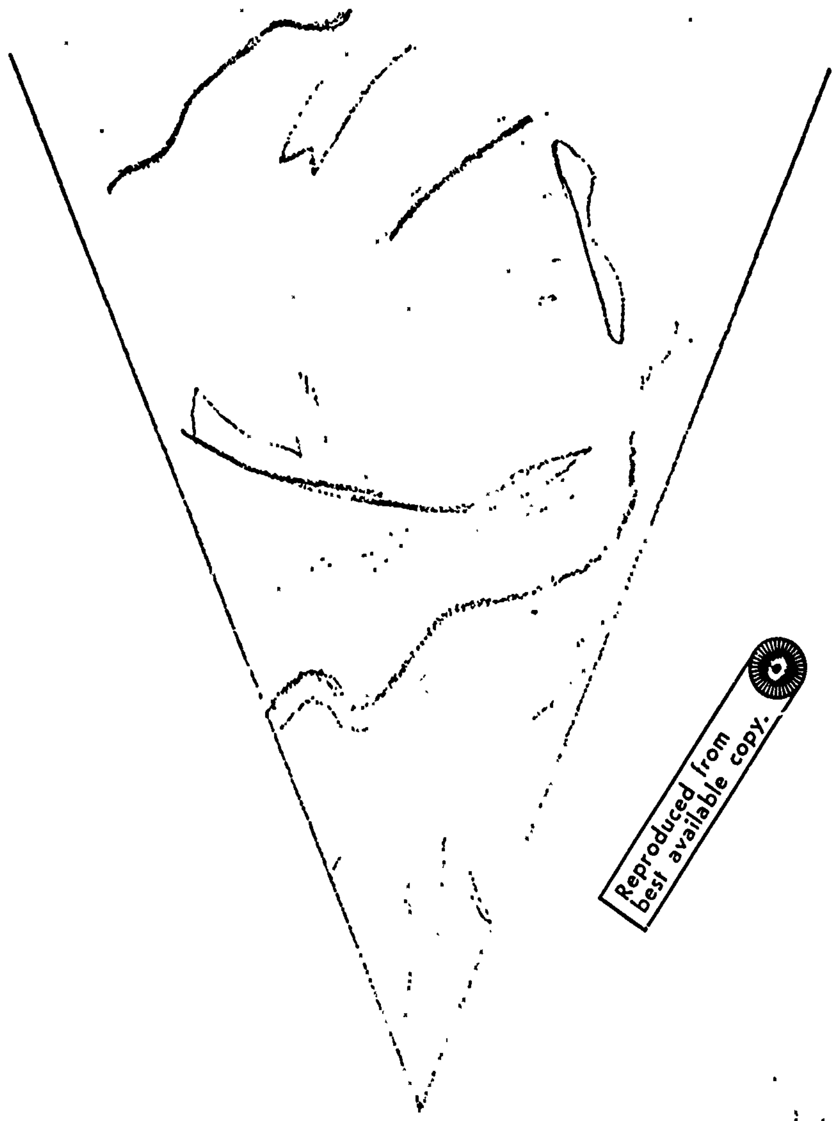


FIGURE 16

RADAR PREDICTION FOR COFFIN ROCKS, PENNSYLVANIA

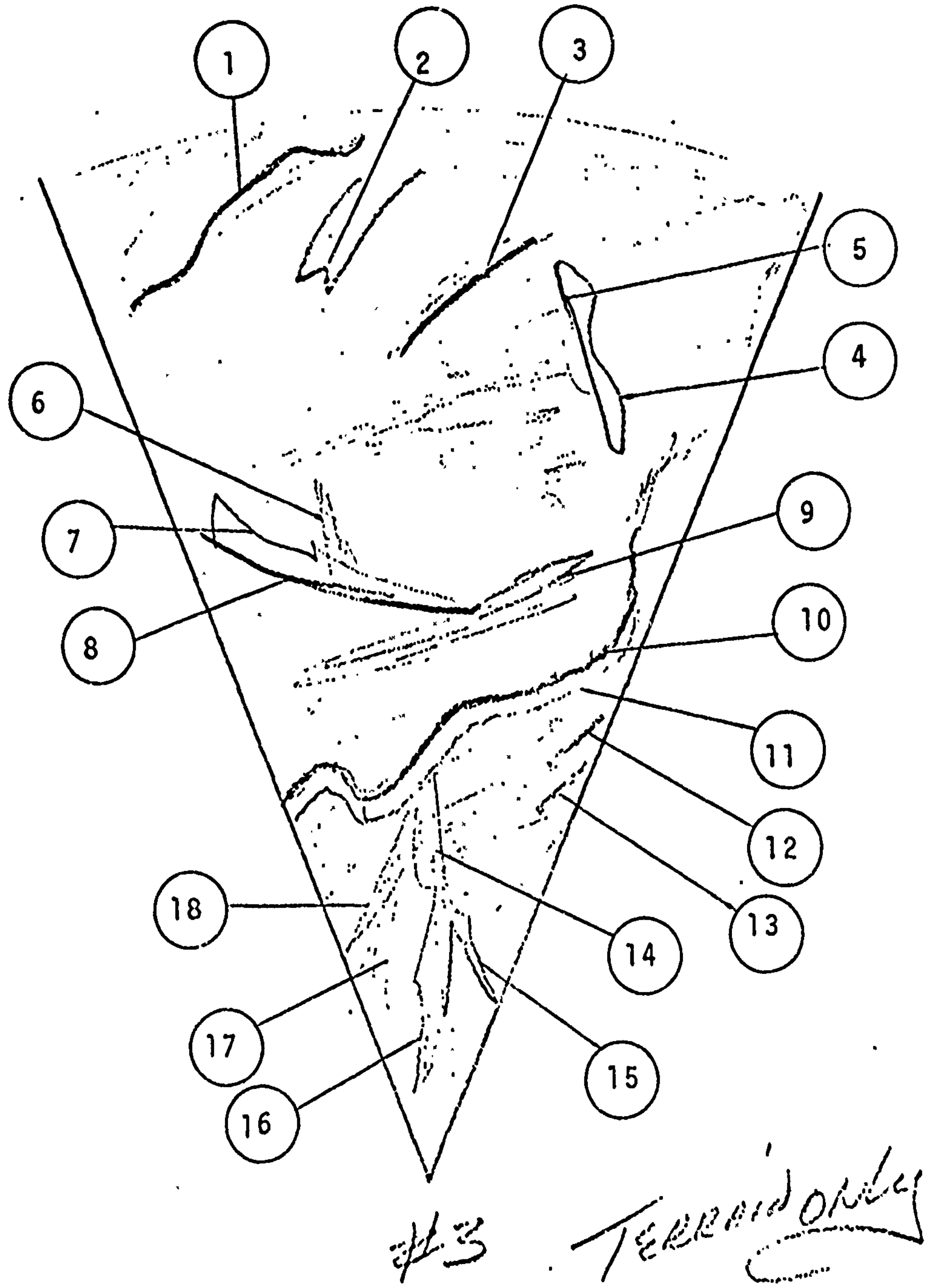


FIGURE 17

RADAR PREDICTION FOR COFFIN ROCKS, PENNSYLVANIA

WITH SIGNIFICANT FEATURES ENUMERATED

FIGURE 18

COMPUTER PLOT OF THE RADAR SHADOW DISPLAY

FOR COFFIN ROCKS, PENNSYLVANIA

USING THE 625' DATA BASE, AIRCRAFT ALTITUDE 3500'

copy of the hand-sketched prediction on top of the computer plot, each significant feature is marked with a colored pencil wherever there is correspondence in both displays.

The degree of correspondence between the computer plot and the hand-sketched prediction is then tabulated. Four possible states are:

STATE	DESCRIPTION
(A)	Completely recognizable.
(B)	Approximately 3/4 of the feature recognizable.
(C)	Approximately 1/2 of the feature recognizable.
(D)	Feature unrecognizable or missing.

Features which appeared on the computer plots but not in the predictions were not considered in this tabulation since such features may or may not have been valid independent of the fact that the radar operators would not use them for navigation.

Tables 9, 10, 11 and 12 tabulate the results for the four geographical areas of interest. For the Coffin Rocks, Pennsylvania area, tabulated in Table 9, there are 18 significant features. The correspondence of each feature, as it appears using each data base, is given. The evaluation of the Jersey Shore, Pennsylvania area is given in Table 10, the Lock Haven, Pennsylvania area is given in Table 11 and the Wilkes Barre, Pennsylvania area is given in Table 12.

TABLE 9

COMPARISON OF RADAR SIGNIFICANT FEATURES
FOR COFFIN ROCKS, PENNSYLVANIA

FEATURE NUMBER		Reference	DATA BASE 625 ft	1250 ft	1875 ft	Modified Lagrange
1		A	A	A	A	C
2		A	A	A	A	A
3		A	A	A	A	A
4		A	D	D	D	B
5		A	A	A	A	A
6		A	A	D	D	D
7		A	A	A	C	A
8		A	A	A	C	A
9		A	A	A	A	A
10		A	A	A	A	A
11		A	A	A	A	A
12		A	A	D	A	A
13		A	A	D	D	A
14		A	A	A	A	A
15		A	A	A	D	A
16		A	A	D	D	D
17		D	D	D	D	D
18		A	A	A	C	A
Total Number of	A's	17	16	12	8	13
	B's	0	0	0	0	1
	C's	0	0	0	4	1
	D's	1	2	6	6	3

TABLE 10

COMPARISON OF RADAR SIGNIFICANT FEATURES
FOR JERSEY SHORE, PENNSYLVANIA

FEATURE NUMBER		Reference	DATA BASE 625 ft	1250 ft	1875 ft	Modified Lagrange
1		A	A	A	A	A
2		A	A	C	C	B
3		A	A	A	D	A
4		B	C	D	A	D
5		C	C	D	D	D
6		A	C	C	D	C
7		A	A	A	A	D
8		A	A	A	A	D
9		A	A	C	C	B
10		A	D	D	D	D
11		A	B	A	A	B
12		A	B	D	D	D
13		C	C	C	D	B
14		A	A	C	C	A
15		A	A	A	A	A
16		C	D	D	D	D
Total	A's	12	8	6	6	4
Number	B's	1	2	0	0	4
of	C's	3	4	5	3	1
	D's	0	2	5	7	7

TABLE 11

COMPARISON OF RADAR SIGNIFICANT FEATURES
FOR LOCK HAVEN, PENNSYLVANIA

FEATURE NUMBER		Reference	DATA BASE 625 ft	1250 ft	1875 ft	Modified Lagrange
1		A	A	A	B	C
2		A	A	A	A	A
3		A	A	C	A	D
4		A	A	A	C	B
5		A	A	A	A	A
6		A	A	A	A	C
7		A	A	A	A	A
8		A	A	A	A	C
9		A	A	A	A	C
10		A	A	A	A	A
11		A	A	A	A	A
12		A	A	A	A	A
13		A	C	D	D	D
14		A	A	D	D	D
15		A	A	A	A	C
16		A	A	A	A	D
17		A	A	A	A	D
18		A	A	D	D	A
19		A	A	A	A	A
20		C	D	C	C	B
Total	A's	19	18	15	14	8
Number	B's	0	0	0	1	2
of	C's	1	1	2	2	5
	D's	0	1	3	3	5

TABLE 12

COMPARISON OF RADAR SIGNIFICANT FEATURES
FOR WILKES BARRE, PENNSYLVANIA

FEATURE NUMBER		Reference	DATA BASE 625 ft	DATA BASE 1250 ft	DATA BASE 1875 ft	Modified Lagrange
1		A	A	A	C	B
2		A	A	A	A	A
3		A	A	A	C	B
4		A	A	A	A	A
5		D	D	D	A	A
6		A	A	B	C	A
7		A	A	A	A	A
8		A	A	A	C	C
9		C	A	A	D	A
10		C	B	C	D	D
11		A	D	A	C	D
12		D	D	D	D	D
13		D	D	D	D	D
14		D	D	D	D	D
Total Number of	A's	8	8	8	4	6
	B's	0	1	1	0	2
	C's	2	0	1	5	1
	D's	4	5	4	5	5

The Ranking

The first step in ranking each data compression technique was to find the total number of each state of correspondence associated with each data base, summing over the four geographical areas. The degree of correspondence for each data base is given in Table 13.

The following weights are assigned to each state of correspondence:

(A) = +1.0

(B) = +0.75

(C) = +0.50

(D) = -1.0

The overall rating for each data compression technique was determined by summing the products of the frequency of occurrence of each state of correspondence times its respective weight. The resultant rating and the rank associated with each data compression technique is given in Table 14.

Case Studies

The objective evaluation discussed in Chapter III was performed for each of 60 radar shadow displays. The 60 radar shadow displays were the result of considering 4 geographical locations at 3 aircraft altitudes for the 5 types of data bases, i.e., source data base, 625 ft, 1250 ft and 1875 ft data bases and the modified Lagrange polynomial data base. The 60 radar shadow displays are grouped into 12

TABLE 13

FREQUENCY OF OCCURRENCE FOR EACH STATE OF CORRESPONDENCE BY DATA BASE

STATE OF CORRESPONDENCE	Reference	DATA BASE 625 ft	1250 ft	1875 ft	Modified Lagrange
A	56	50	41	32	31
B	1	3	1	1	9
C	6	5	8	14	8
D	5	10	18	21	20

TABLE 14

RANK OF DATA COMPRESSION TECHNIQUES
(Subjective Evaluation)

DATA BASE	Reference	625 ft	1250 ft	1875 ft	Modified Lagrange
RATING	54.75	44.75	27.75	18.75	21.75
RANK	No Rank Assigned	1	2	4	3

case studies. A single case study provides a comparison of the shadow displays for each type of data base for the same aircraft location, heading and altitude.

The four measures of "goodness," i.e., the weighted error, connectedness, shadow loss and shadow gain, are computed for each radar shadow display. The performance criterion is computed from these four measures and the selected set of weighting constants; $K_1 = 0.5$, $K_2 = 0.2$, $K_3 = 0.2$, $K_4 = 0.1$.

These 12 case studies and the respective radar shadow displays are presented in Appendix B.

A Comparison of Results

Using the magnitude of the objective performance criterion as the overall measure of "goodness," a rating of each data compression technique was made. Table 15 gives the frequency distribution of "goodness" rating for each of the four data compression techniques based on the 12 case studies given in Appendix B.

From the distribution given in Table 15 it is concluded that the general ranking given to each data compression technique is:

625 ft. . . . ."best"

1250 ft . . . ."second best"

Modified Lagrange Polynomial . . ."third best"

1875 ft . . . ."fourth best."

TABLE 15

FREQUENCY DISTRIBUTION OF
OBJECTIVE PERFORMANCE RATINGS

Rating	625 ft	1250 ft	1875 ft	Modified Lagrange Polynomial
1st of 4	12	0	0	0
2nd of 4	0	9	1	2
3rd of 4	0	3	3	6
4th of 4	0	0	8	4

The ranking of each data compression technique by the subjective evaluation is presented in Table 14 and the ranking of each technique by the terrain RMS error criterion is presented in Chapter IV. These rankings, along with the ranking for the objective evaluation and compression ratio achieved, are summarized in Table 16.

A comparison of the results obtained by either the objective or subjective method with that obtained by the terrain RMS error criterion supports the hypothesis that averaging-type measures such as the RMS error are not directly related to the usefulness of the simulated radar displays. The fact that connectedness was found to be a detriment by both the subjective and objective evaluation methods while it was found to be beneficial by the terrain RMS error criterion accounts for the failure of the terrain RMS error criterion to effectively measure the "goodness" of the data compression techniques.

The ratings given in Table 16 do not take into consideration the data compression ratio achieved. It is interesting to observe that the ratings given by the subjective and objective evaluations are in the inverse order of a rating which would be obtained based solely on the magnitude of the compression ratio. In this research, however, the primary consideration is the quality, or "goodness," of the simulated radar displays. Since the data compression achieved has a direct bearing on the cost of a resultant digital radar landmass simulator, a cost

TABLE 16

A COMPARISON OF THE EVALUATION RATINGS

EVALUATION TECHNIQUES	625 ft	1250 ft	1875 ft	Lagrange Polynomial
RMS Error of Terrain Profiles	2nd	3rd	4th	1st
Objective Evaluation	1st	2nd	4th	3rd
Subjective Evaluation	1st	2nd	4th	3rd
Data Compression Ratio	9:1	36:1	81:1	64:1

effectiveness trade-off between the data compression achieved and the quality of the simulated radar display can be performed when the data compression technique is selected.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

All the goals set forth for this research have been satisfied. A facility for the generation of radar shadow displays from various terrain data bases has been developed. Radar shadow displays were generated utilizing different data compression techniques as well as no data compression. This made possible, for the first time, a comparison of the radar displays generated with different data compression techniques and radar displays generated without the use of data compression.

An objective method for the evaluation of terrain data compression techniques has been established and confirmed for twelve case studies by subjective evaluations by experienced radar operators. The subjective evaluation technique which was developed in this research provides a systematic approach for defining the radar navigator's radar display requirements for navigation, comparing these requirements with simulated radar displays and finally scoring the simulated displays.

The objective evaluation method, supported by the subjective evaluations, has demonstrated the inadequacy of the currently used terrain RMS error criterion for specifying the "goodness" of terrain data compression techniques.

The objective evaluation method makes use of a performance criterion which consists of the weighted sum of four measures of "goodness." These measures are weighted error, connectedness, shadow loss and shadow gain and rate the resultant radar shadow display directly. The rating of the data base and data compression technique is in terms of their effect on the simulated radar displays. The converse, rating the data compression technique or the data base directly, with an implied rating of the final radar display, is exemplified by the terrain RMS error criterion as a measure of "goodness." The direct rating of the final radar display puts the evaluation in terms of the user's requirements instead of the theoretical considerations of the data compression techniques.

The contribution to the performance criterion by each "goodness" measure is specified by the selection of the respective weighting constant. This makes possible the tailoring of the performance criterion to the particular radar training application.

It is particularly worth noting the development of the "goodness" measure for connectedness. The results obtained with this measure speak both a warning of possible radar trainer failures and of a requirement for the development of a set of "goodness" measures based on a thorough investigation of the radar operator's requirements for accuracy as well as realism in the simulated radar displays and the understanding of the data compression techniques under investigation. The tool pro-

posed and implemented in this research for the generation of radar shadow displays spurred the development of the connectedness measure. The connectedness measure effectively determines the amount of distortion introduced in the shape of the radar shadows by the polynomial data compression technique. Although the use of polynomials has been advocated for the compression of radar terrain data since 1962 [2], and the modified Lagrange polynomial has been touted as the "ultimate" terrain data compression polynomial since 1966 [6], the degrading effects introduced by polynomial data compression were not demonstrated until this study. The possibility exists that other such effects are present in others of the presently proposed terrain data compression techniques and may be present in those of the future.

It is recommended prior to the implementation of any terrain data compression techniques in a radar landmass simulator that the technique be investigated in the manner demonstrated by this thesis; that is, a nonreal-time simulation and objective performance analysis based on the particular training requirements. Such an investigation would hopefully help prevent any unfavorable receptions by the users when the trainer is delivered to the training facility.

Topics for Future Study

During the course of this work a number of topics arose which were quite interesting, and appear to be worthy of further study. However, the pursuit of these topics is beyond the scope of this work.

Therefore, these topics are collected here for the purpose of providing apparently worthwhile ideas for extension or modification of this work. These areas are:

(1) The application of evaluation methods similar to those developed in this thesis to the other currently proposed terrain data compression techniques [15]. This is particularly true for data compression techniques such as the planar surface [15] approach where the technique is basically different from the two types of data compression evaluated in this thesis.

(2) The evaluation method developed in this thesis should be expanded to include the evaluation of data compression techniques used in other radar simulation applications such as terrain avoidance or terrain following. This would involve the development of new measures of "goodness" which would relate the

required radar display parameters to the data compression technique.

(3) The development of more effective terrain data compression techniques. Effective terrain data compression is achieved when most, if not all, of the radar significant information, that is, the terrain information which contributes to the quality of the resultant radar display, is retained while the remainder is eliminated. In another sense, the effectiveness of data compression is measured by the magnitude of the compression ratio. While the compression ratios for the techniques studied in this thesis, as well as the other currently proposed techniques, are less than one-hundred to one the anticipated improvements in radar capability will dictate improvements of possibly several orders of magnitude in the effectiveness of terrain data com-

pression. The development of more effective terrain data compression techniques should involve determining what portion of the terrain information is radar significant possibly through the application of more classical data compression methods such as frequency analysis. The use of frequency domain type data compression looks most attractive in light of the recent development of inexpensive Fast Fourier Transform digital processors.

APPENDICES

APPENDIX A

DATA FORMATS AND FILE STRUCTURES

Maximum Sample Algorithm and Tape Formats

The data formats of the magnetic tapes used in the processing of the maximum sample algorithm, as shown in Figure 9, are given in Table 17. The input data to the maximum sample algorithm are the source terrain elevation data (STE), also called the reference data base. Each record of the STE data tape contains the terrain elevation for 208.33 ft x 208.33 ft squares on a line drawn approximately south to north across the digitally stored terrain map. The next record corresponds to a similar line which is drawn 208.33 ft to the east of the prior line.

In order to conserve magnetic tape and to reduce the handling of these terrain elevation tapes the data is packed two elevations per word with each terrain elevation stored as a 16-bit half-word. It is then necessary to unpack the terrain elevations prior to their use by the maximum sample algorithm.

Data Base Parameters

The three data bases generated using the maximum sample algorithm were divided into regions and placed on a single magnetic tape as three separate files. The data base parameters associated with

TABLE 17

THE MAXIMUM SAMPLE DATA BASES - TAPE FORMAT

TAPE	FORMAT
SOURCE TERRAIN ELEVATION DATA	7938 - 1036 word records* in two volumes
625 ft DATA BASE	2646 - 688 word records
1250 ft DATA BASE	1323 - 344 word records
1875 ft DATA BASE	882 - 230 word records
625 ft - 1250 ft - 1875 ft DATA BASE IN 24 x 24 ELEMENT REGIONS	1st file - 3219 - 577 word records 2nd file - 840 - 577 word records 3rd file - 370 - 577 word records

*Data packed two terrain elevations per word. (e text).

the 71 NM x 276 NM area of interest are given in Table 18. The number of words stored per region is 577; 24 x 24 elevations per region plus a region number.

The reference data base was also divided into 24 x 24 resolution element regions and stored on two additional volumes of magnetic tape. The data base parameters for the reference data base is also given in Table 18. The number of words stored per region is 289; 24 x 24 elevation words per region plus a region number. The elevations are packed two per word.

The modified Lagrange polynomial data base consists of 36 coefficients per 5000 ft x 5000 ft region. The data base parameters associated with this data base are given in Table 18. The number of words stored per region is 19; 36 coefficients packed two per word plus a region number.

Terrain Profile File Structure

Each terrain profile file is made up of a two-word record containing the scan number and resolution followed by 90 binary records consisting of 576 words; one word per elevation value. Each magnetic tape consists of a file management file followed by the various radar scan files. All files are separated by end-of-file marks. The file management file contains the dictionary to the files and a count of the number of files on the tape.

TABLE 18

DATA BASE PARAMETERS

Resolution	Number of Regions in West to East Direction	Number of Regions in South to North Direction	Number of Words per Region	Number of Words (32-bit) in Data Base
208.33 ft (Reference)	331	86	289[1]	8,146,674
625 ft	110	28	577	1,777,160
1250 ft	55	14	577	444,290
1875 ft	36	9	577	186,948
Modified Lagrange Polynomial	331	86	19[2]	483,922

Note: 1 - Data packed two elevations per word
2 - Polynomial coefficients packed two coefficients per word

Incorporated into each program which has to either read or write on the file tapes is a short Fortran routine which interrogates the file management file and through the use of the "Buffer In" routine [18], spaces the tape to the appropriate file. This spacing routine makes use of the end-of-file mark to determine the end of each file.

Shadow Profile File Structure

A file structure and maintenance system similar to that used for the storage of the terrain elevation data is used for the storage of the radar shadow data. Each file consists of two words which contain the file identification and resolution information followed by 90 binary records, each containing the data for a single simulated radar sweep. Each record contains 576 words, one word per display element. Each word is either 0 or 1 to represent shadow or nonshadow respectively.

Each magnetic tape consists of a file management file followed by the various radar scan files. All files are separated by end-of-file marks. The file management file contains the dictionary to the files and a count of the number of files on the tape.

Incorporated into each program which has to either read or write on the file tapes is a short Fortran routine which interrogates the file management file and through the use of the "Buffer In" routine [18], spaces the tape to the appropriate file. This spacing routine makes use of the end-of-file mark to determine the end of each file.

APPENDIX B

CASE STUDIES

The objective evaluation discussed in Chapter III was performed for each of 60 radar shadow displays. The 60 radar shadow displays were the result of considering 4 geographical locations at 3 aircraft altitudes for the 5 types of data bases, namely, the source data base, the 625 ft, 1250 ft and 1875 ft data bases and the modified Lagrange polynomial data base. The 60 radar shadow displays are grouped into 12 case studies. A single case study provides a comparison of the shadow displays for each type of data base for the same aircraft location, heading and altitude.

The four measures of "goodness," the weighted error, connectedness, shadow loss and shadow gain, are computed for each radar shadow display. The performance criterion is computed from these four measures and the selected set of weighting constants; $K_1 = 0.5$, $K_2 = 0.2$, $K_3 = 0.2$, $K_4 = 0.1$.

These 12 case studies are presented on 12 case summary sheets below and the respective radar shadow displays are presented in Figure 19 through Figure 30.

CASE STUDY SUMMARY SHEET

CASE NUMBER 1

RADAR SHADOW DISPLAY Figure 19

AREA Wilkes Barre, Pennsylvania

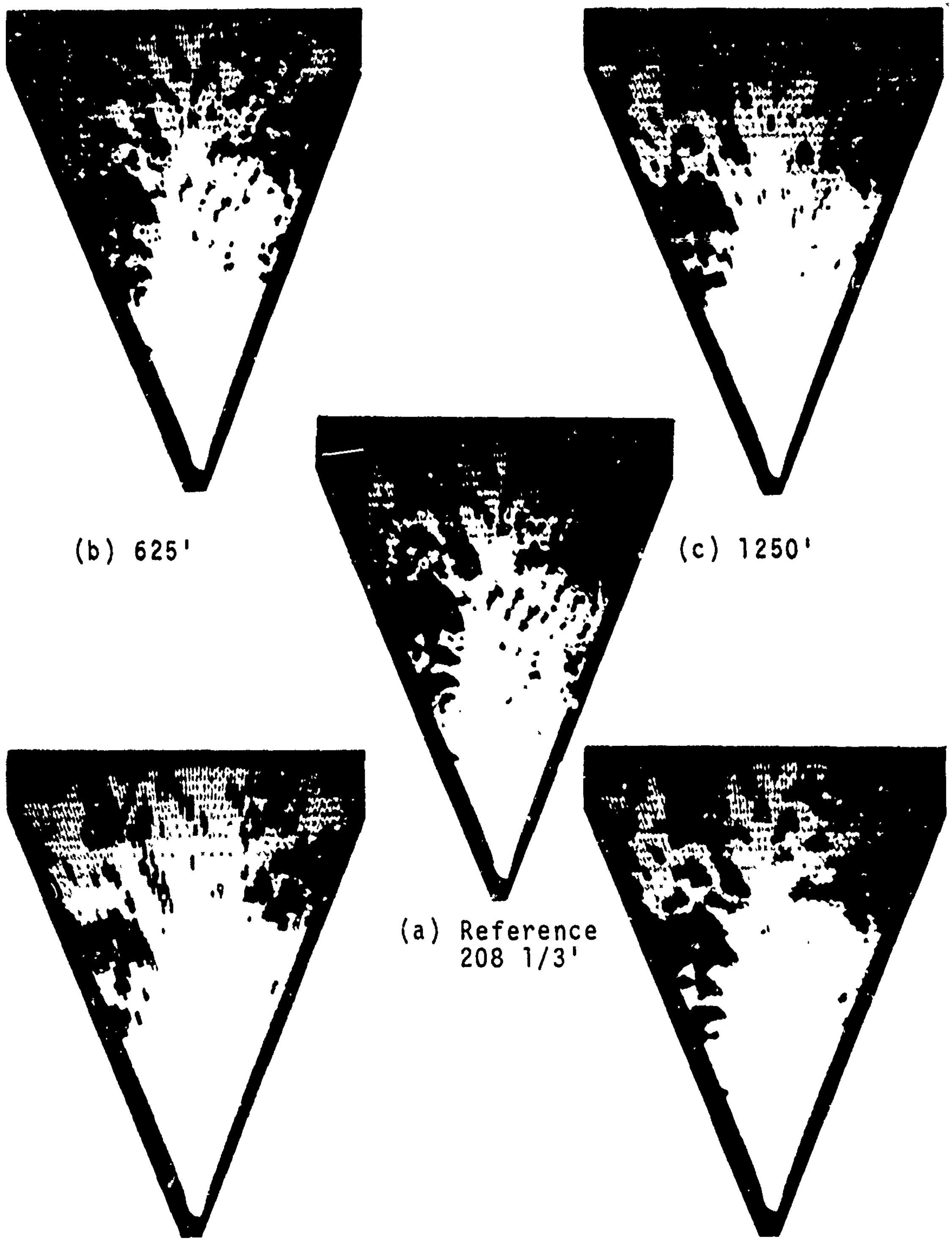
AIRCRAFT PARAMETERS

POSITION	41°12'	North Latitude
	75°57'	West Longitude
HEADING	45°	
ALTITUDE	3500'	

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.055338	0.088822	0.117071	0.079590
CONNECTEDNESS	0.002219	0.038209	0.006881	0.258030
SHADOW LOSS	0.046624	0.089005	0.125424	0.078627
SHADOW GAIN	0.025540	0.026427	0.026736	0.024769
NORMALIZED* PERFORMANCE CRITERIA	0.068585	0.124330	0.150353	0.187968

* A combined error measure, scale 0.0 to 1.0



(b) 625'

(c) 1250'

(a) Reference
208 1/3'

(d) 1875'

(e) Modified Lagrange
Polynomial
5000' Regions

FIGURE 19

RADAR SHADOW DISPLAY, WILKES BARRE, PA. AIRCRAFT ALTITUDE 3500'

CASE STUDY SUMMARY SHEET

CASE NUMBER 2

RADAR SHADOW DISPLAY Figure 20

AREA Wilkes Barre, Pennsylvania

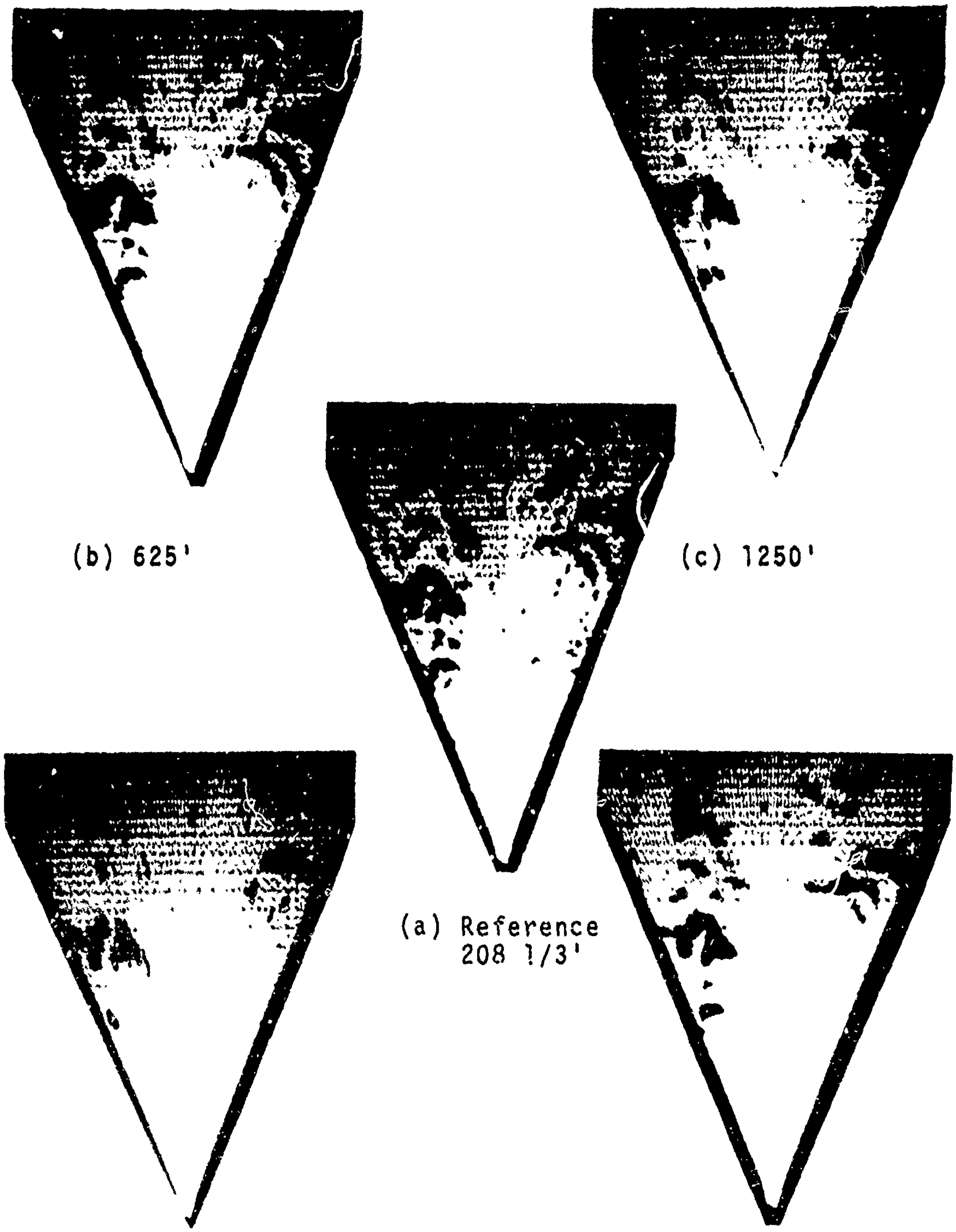
AIRCRAFT PARAMETERS

POSITION	$41^{\circ}12'$	North Latitude
	$75^{\circ}57'$	West Longitude
HEADING	45°	
ALTITUDE	7000'	

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.027206	0.041955	0.052831	0.036155
CONNECTEDNESS	0.087654	0.114255	0.004548	0.286107
SHADOW LOSS	0.042033	0.073380	0.098032	0.065355
SHADOW GAIN	0.014776	0.013889	0.011921	0.010012
NORMALIZED* PERFORMANCE CRITERIA	0.070346	0.102716	0.082532	0.153270

* A combined error measure, scale 0.0 to 1.0



(b) 625'

(c) 1250'

(a) Reference
208 1/3'

(d) 1875'

(e) Modified Lagrange
Polynomial
5000' Regions

FIGURE 20

RADAR SHADOW DISPLAY, WILKES BARRE, PA. AIRCRAFT ALTITUDE 7000'

CASE STUDY SUMMARY SHEET

CASE NUMBER 3

RADAR SHADOW DISPLAY Figure 21

AREA Wilkes Barre, Pennsylvania

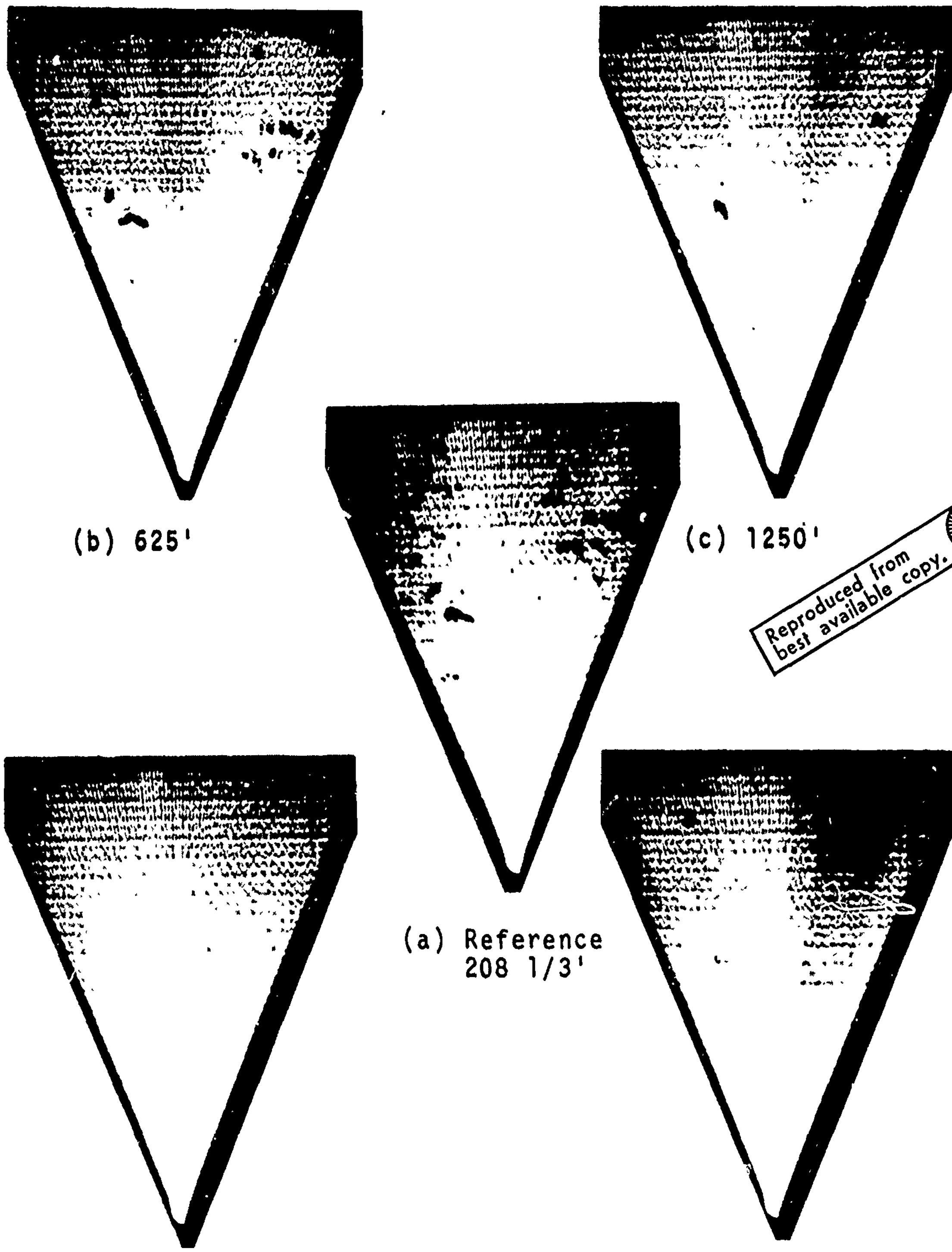
AIRCRAFT PARAMETERS

POSITION	41°12'	North Latitude
	75°57'	West Longitude
HEADING	45°	
ALTITUDE	20,000'	

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.000805	0.000975	0.000992	0.000904
CONNECTEDNESS	0.203953	0.248393	1.000000	0.233879
SHADOW LOSS	0.014448	0.019753	0.021470	0.018576
SHADOW GAIN	0.002990	0.001408	0.000000	0.001042
NORMALIZED* PERFORMANCE CRITERIA	0.076114	0.093051	0.351212	0.087545

* A combined error measure, scale 0.0 to 1.0



(b) 625'

(c) 1250'

(a) Reference
208 1/3'

(d) 1875'

(e) Modified Lagrange
Polynomial
5000' Regions

FIGURE 21

RADAR SHADOW DISPLAY, WILKES BAKRE, PA. AIRCRAFT ALTITUDE 20,000

CASE STUDY SUMMARY SHEET

CASE NUMBER 4

RADAR SHADOW DISPLAY Figure 22

AREA Lock Haven, Pennsylvania

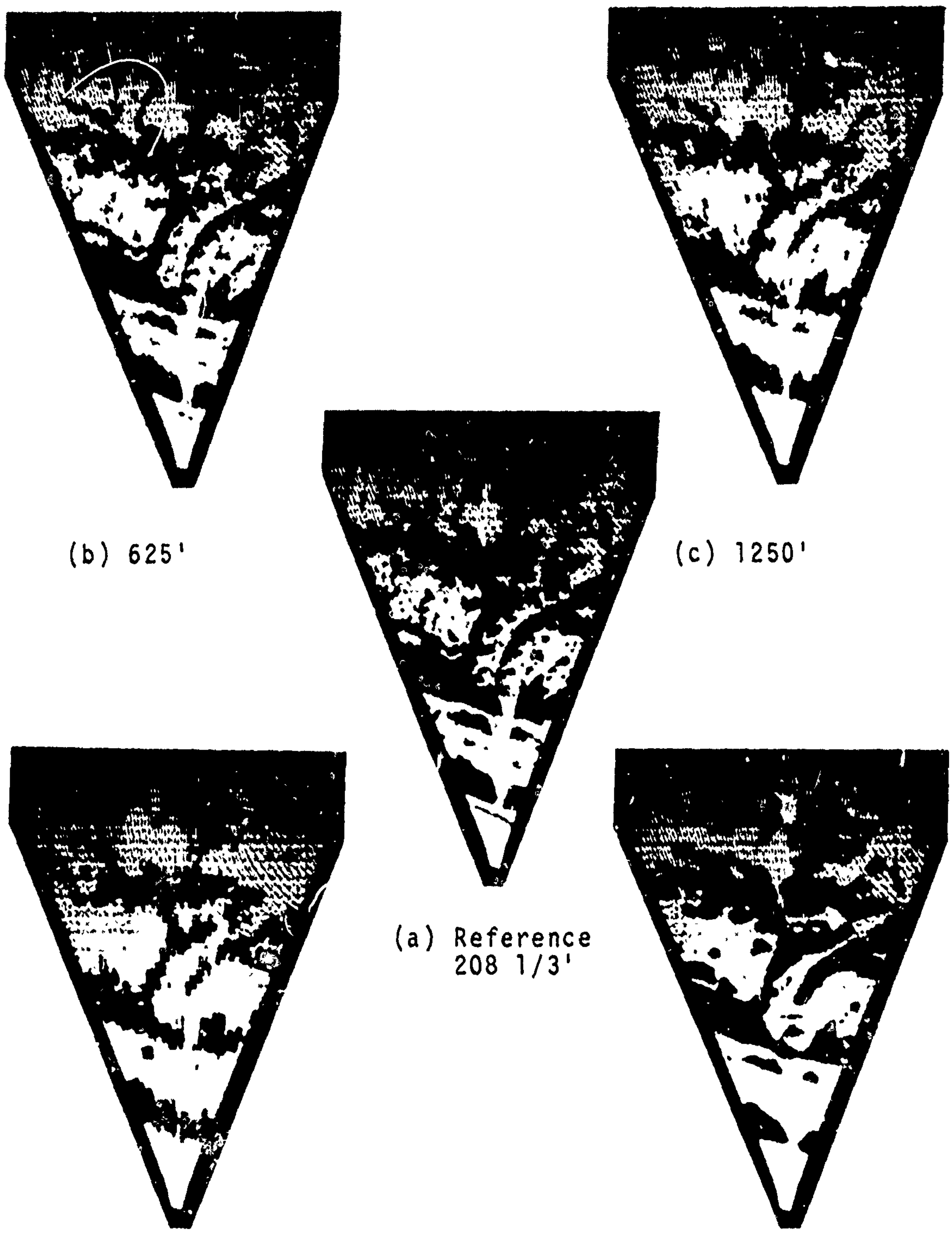
AIRCRAFT PARAMETERS

POSITION	41°5'	North Latitude
	77°23'	West Longitude
HEADING	315°	
ALTITUDE	3500'	

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.104267	0.185549	0.251084	0.123452
CONNECTEDNESS	0.033821	0.024137	0.004166	0.295036
SHADOW LOSS	0.090471	0.182369	0.254861	0.121971
SHADOW GAIN	0.049363	0.068287	0.086381	0.044626
NORMALIZED* PERFORMANCE CRITERIA	0.140506	0.241648	0.318962	0.256553

* A combined error measure, scale 0.0 to 1.0



(b) 625'

(c) 1250'

(a) Reference
208 1/3'

(d) 1875'

(e) Modified Lagrange
Polynomial
5000' Regions

FIGURE 22

RADAR SHADOW DISPLAY, LOCK HAVEN, PA. AIRCRAFT ALTITUDE 3500'

CASE STUDY SUMMARY SHEET

CASE NUMBER 5

RADAR SHADOW DISPLAY Figure 23

AREA Lock Haven, Pennsylvania

AIRCRAFT PARAMETERS

POSITION	$41^{\circ}5'$	North Latitude
	$77^{\circ}23'$	West Longitude
HEADING	315°	
ALTITUDE	7000'	

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

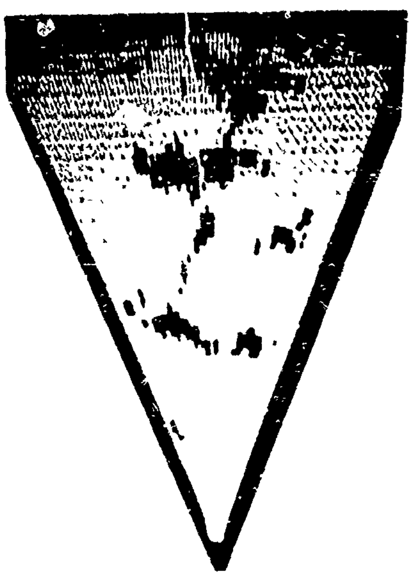
DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.064575	0.102980	0.123628	0.066824
CONNECTEDNESS	0.010140	0.020427	0.098283	0.301121
SHADOW LOSS	0.094174	0.171181	0.220100	0.111497
SHADOW GAIN	0.043017	0.048611	0.043191	0.029012
NORMALIZED* PERFORMANCE CRITERIA	0.098530	0.162362	0.222622	0.203803

* A combined error measure, scale 0.0 to 1.0

(b) 625'

(c) 1250'

(a) Reference
208 1/3'



(d) 1875

(e) Modified Lagrange
Polynomial
5000' Regions

FIGURE 23

RADAR SHADOW DISPLAY, LOCK HAVEN,PA. AIRCRAFT ALTITUDE 7000'

CASE STUDY SUMMARY SHEET

CASE NUMBER 6

RADAR SHADOW DISPLAY Figure 24

AREA Lock Haven, Pennsylvania

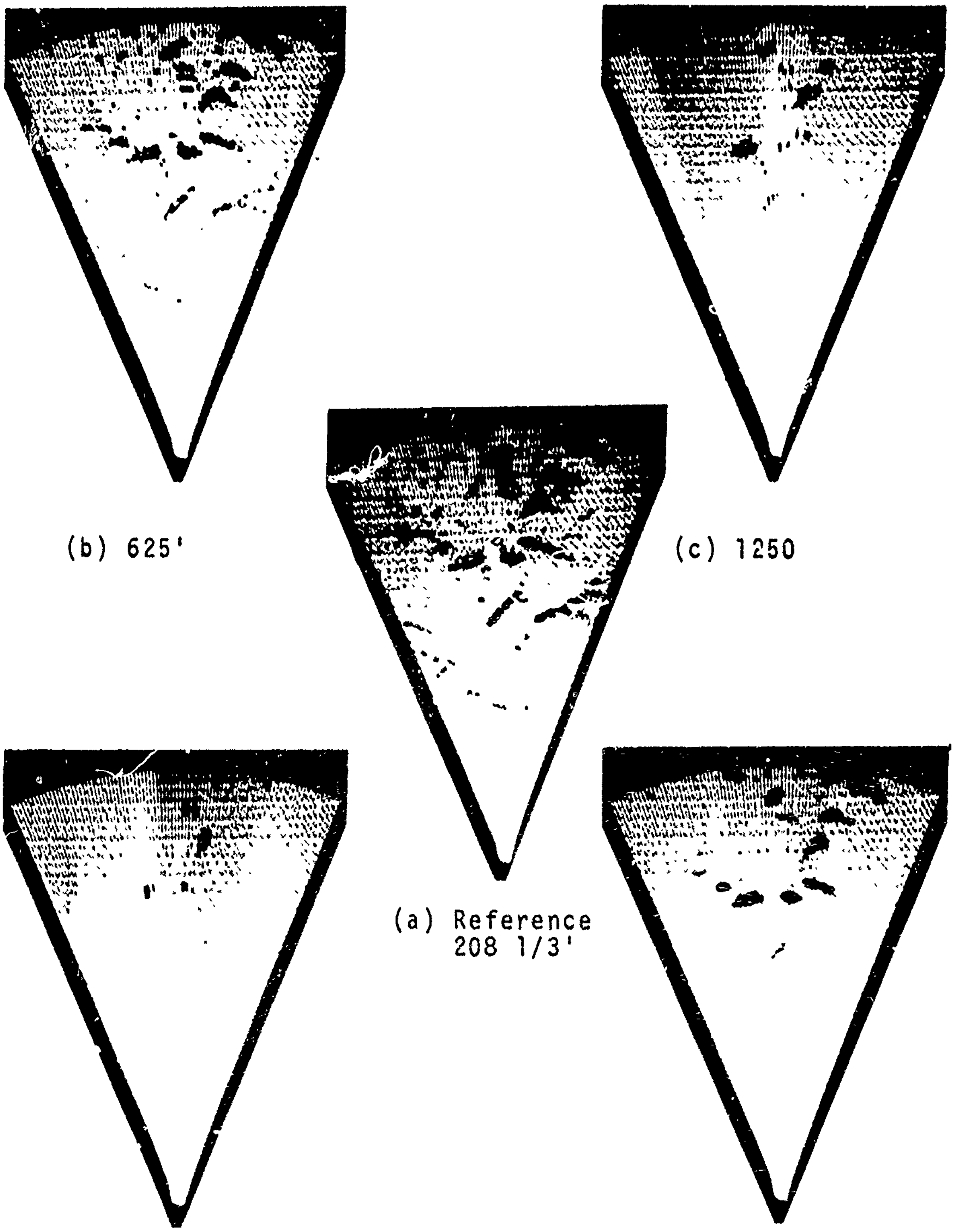
AIRCRAFT PARAMETERS

POSITION	$41^{\circ}5'$	North Latitude
	$77^{\circ}23'$	West Longitude
HEADING	315°	
ALTITUDE	20,000'	

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.002493	0.003212	0.003451	0.002427
CONNECTEDNESS	0.036102	0.076023	0.252273	0.264026
SHADOW LOSS	0.040027	0.062770	0.070216	0.047569
SHADOW GAIN	0.013580	0.006694	0.004765	0.004437
NORMALIZED* PERFORMANCE CRITERIA	0.030579	0.051508	0.193825	0.109719

* A combined error measure, scale 0.0 to 1.0



(b) 625'

(c) 1250

(a) Reference
208 1/3'

(d) 1875

(e) Modified Lagrange
Polynomial
5000' Regions

FIGURE 24

RADAR SHADOW DISPLAY, LOCK HAVEN, PA. AIRCRAFT ALTITUDE 20,000'

CASE STUDY SUMMARY SHEET

CASE NUMBER 7

RADAR SHADOW DISPLAY Figure 25

AREA Jersey Shore, Pennsylvania

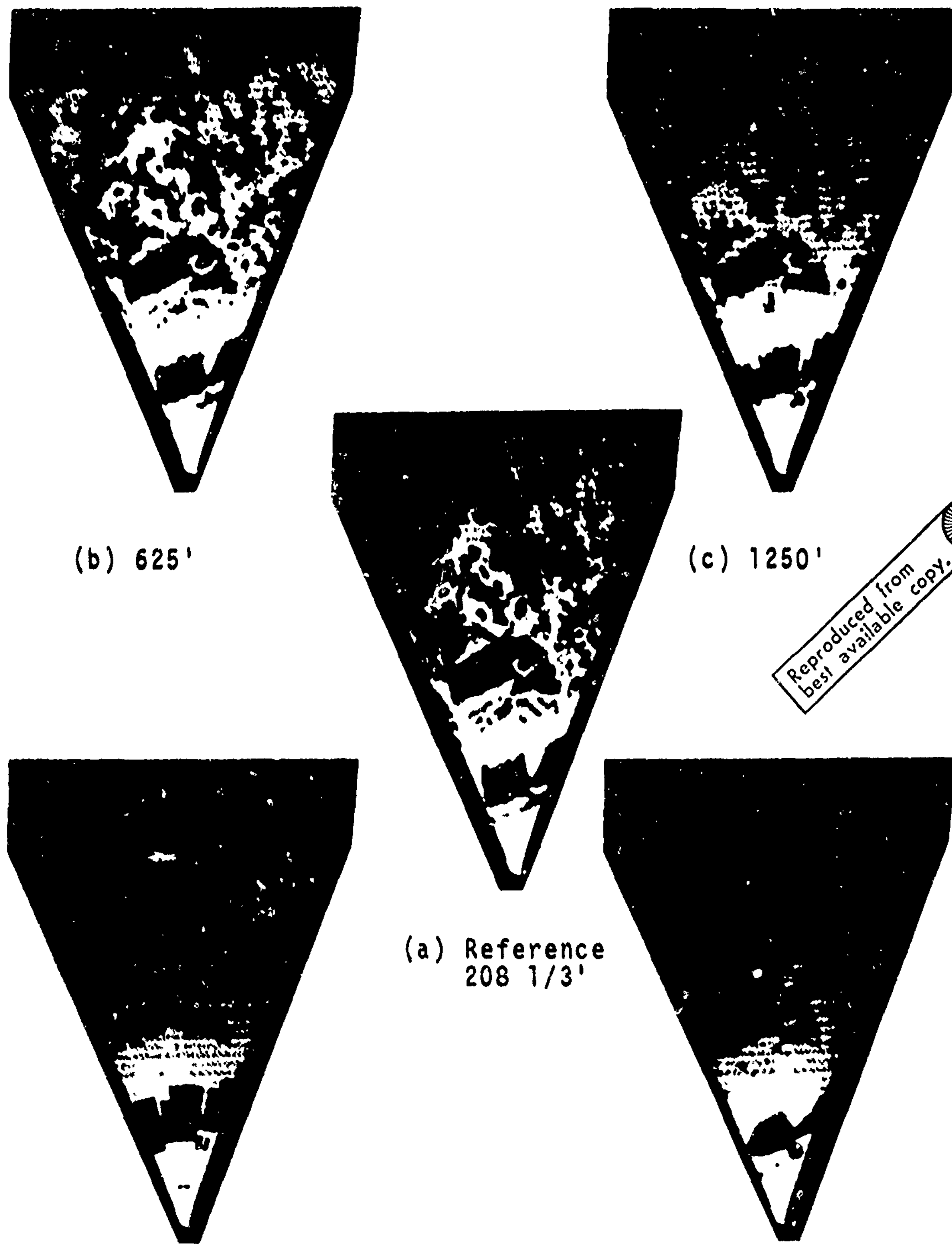
AIRCRAFT PARAMETERS

POSITION	41°6'	North Latitude
	77°17'	West Longitude
HEADING	0°	
ALTITUDE	3500'	

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.088053	0.161713	0.253744	0.133369
CONNECTEDNESS	0.016689	0.051817	0.045123	0.189994
SHADOW LOSS	0.076698	0.157523	0.251755	0.141898
SHADOW GAIN	0.045856	0.069348	0.100791	0.041069
NORMALIZED* PERFORMANCE CRITERIA	0.115571	0.222363	0.336698	0.235244

* A combined error measure, scale 0.0 to 1.0



(b) 625'

(c) 1250'

(a) Reference 208 1/3'

(d) 1875'

(e) Modified Lagrange Polynomial 5000' Regions

FIGURE 25

RADAR SHADOW DISPLAY, JERSEY SHORE, PA. AIRCRAFT ALTITUDE 3500'

CASE STUDY SUMMARY SHEET

CASE NUMBER 8

RADAR SHADOW DISPLAY Figure 26

AREA Jersey Shore, Pennsylvania

AIRCRAFT PARAMETERS

POSITION $41^{\circ}6'$ North Latitude

$77^{\circ}17'$ West Longitude

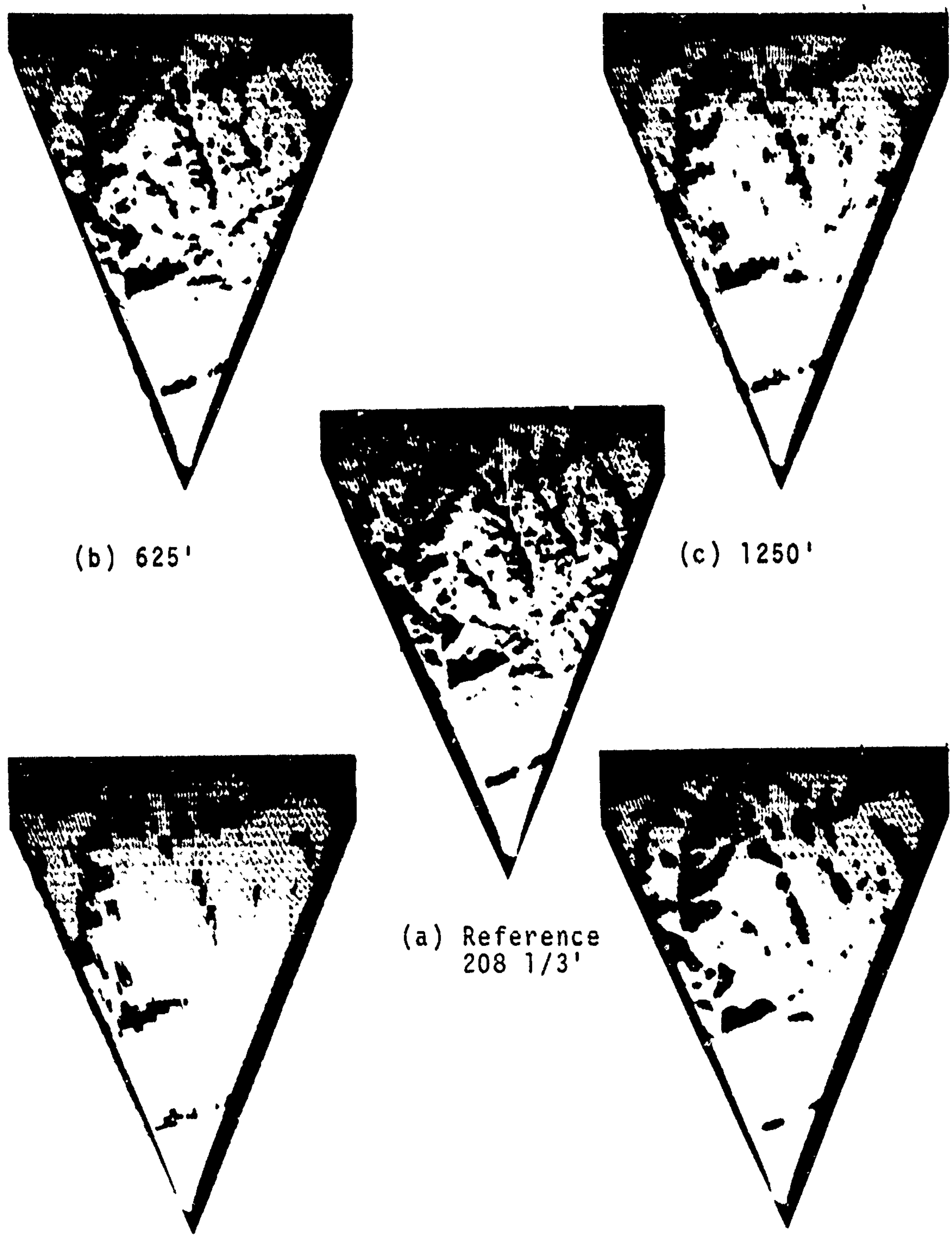
HEADING 0°

ALTITUDE 7000'

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.053727	0.094719	0.129583	0.068766
CONNECTEDNESS	0.015121	0.025254	0.047860	0.241139
SHADOW LOSS	0.080150	0.159568	0.226987	0.123785
SHADOW GAIN	0.034047	0.042978	0.053279	0.021508
NORMALIZED* PERFORMANCE CRITERIA	0.084588	0.151985	0.214525	0.187823

* A combined error measure, scale 0.0 to 1.0



(b) 625'

(c) 1250'

(a) Reference
208 1/3'

(d) 1875'

(e) Modified Lagrange
Polynomial
5000' Regions

FIGURE 26

RADAR SHADOW DISPLAY, JERSEY SHORE, PA. AIRCRAFT ALTITUDE 7000'

CASE STUDY SUMMARY SHEET

CASE NUMBER 9

RADAR SHADOW DISPLAY Figure 27

AREA Jersey Shore, Pennsylvania

AIRCRAFT PARAMETERS

POSITION	$41^\circ 6'$	North Latitude
	$77^\circ 17'$	West Longitude
HEADING	0°	
ALTITUDE	20,000'	

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.002376	-0.003383	0.003724	0.002675
CONNECTEDNESS	0.089299	0.086707	0.476576	0.229737
SHADOW LOSS	0.037847	0.062905	0.077990	0.053299
SHADOW GAIN	0.012982	0.009857	0.002431	0.004147
NORMALIZED* PERFORMANCE CRITERIA	0.047875	0.055908	0.193825	0.100086

* A combined error measure, scale 0.0 to 1.0

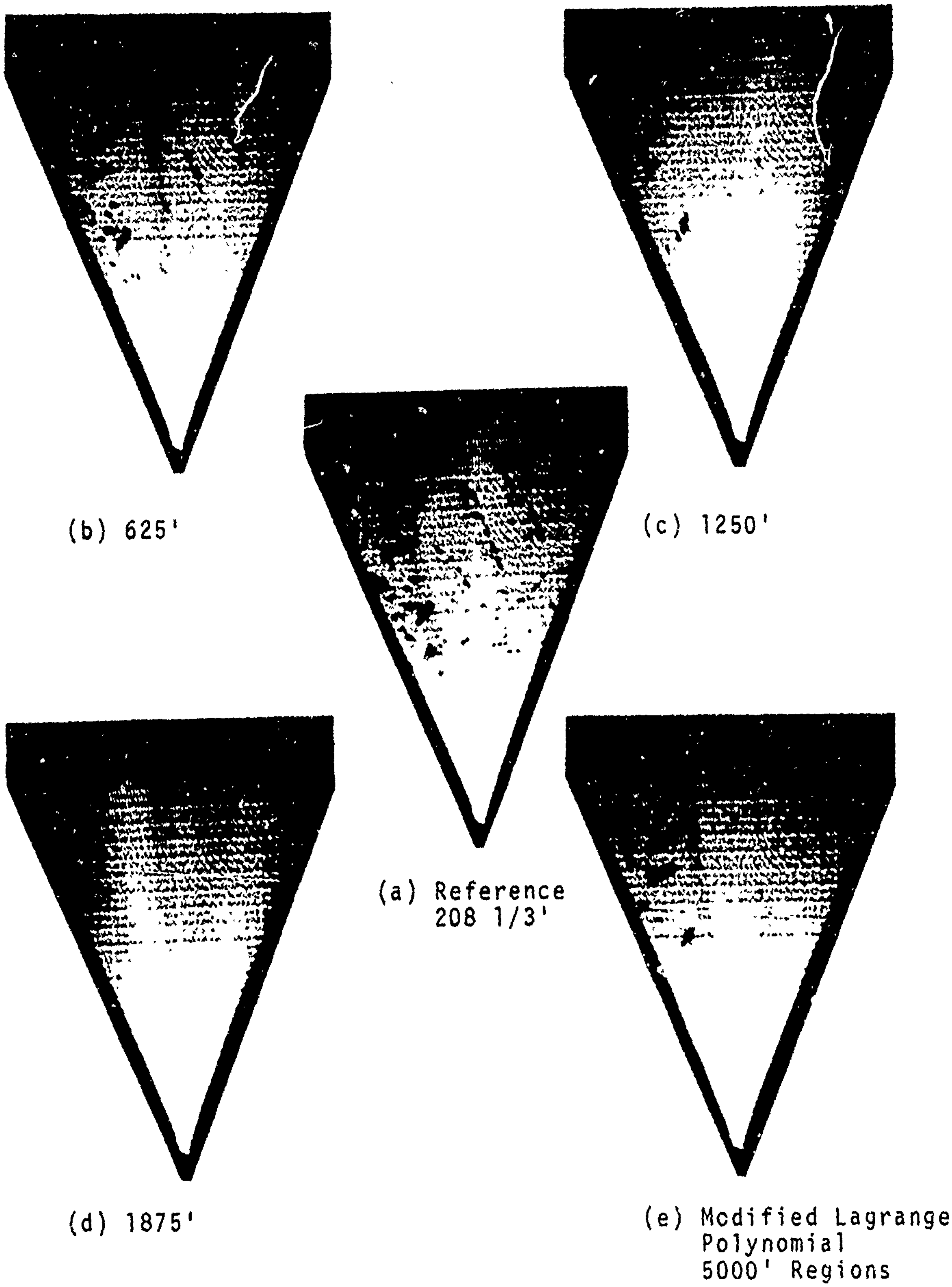


FIGURE 27

RADAR SHADOW DISPLAY, JERSEY SHORE,PA. AIRCRAFT ALTITUDE 20,000'

CASE STUDY SUMMARY SHEET

CASE NUMBER 10

RADAR SHADOW DISPLAY Figure 28

AREA Coffin Rocks, Pennsylvania

AIRCRAFT PARAMETERS

POSITION $41^{\circ}15'$ North Latitude

$77^{\circ}45'$ West Longitude

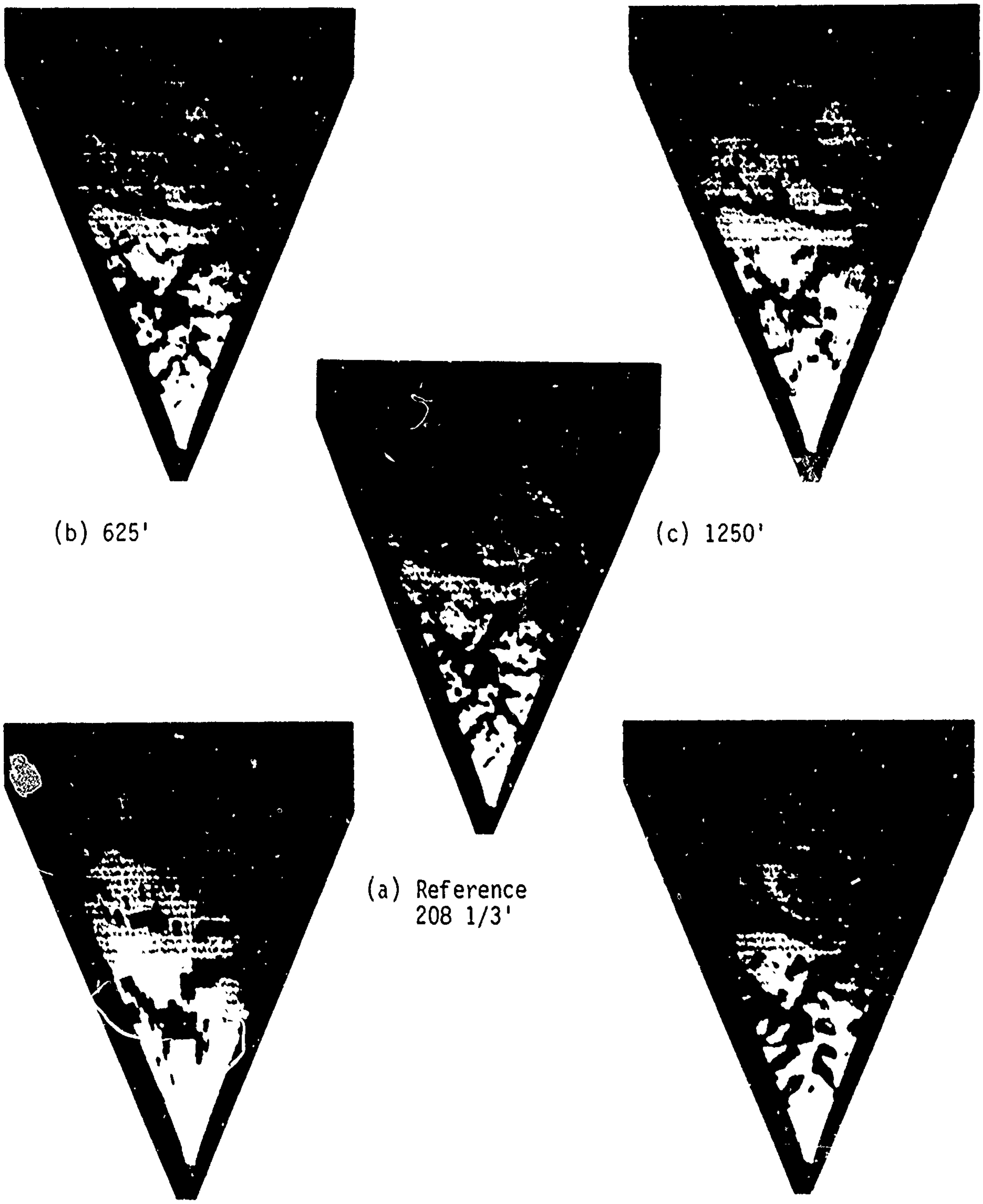
HEADING 90°

ALTITUDE 3500'

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.091508	0.169483	0.214875	0.136414
CONNECTEDNESS	0.085181	0.108225	0.069093	0.243817
SHADOW LOSS	0.090181	0.187481	0.257986	0.119714
SHADOW GAIN	0.037076	0.044792	0.035378	0.067477
NORMALIZED* PERFORMANCE CRITERIA	0.144975	0.254438	0.302508	0.253236

* A combined error measure, scale 0.0 to 1.0



(b) 625'

(c) 1250'

(a) Reference
208 1/3'

(d) 1875'

(e) Modified Lagrange
Polynomial
5000' Regions

FIGURE 28

RADAR SHADOW DISPLAY, COFFIN ROCKS, PA. AIRCRAFT ALTITUDE 3500'

CASE STUDY SUMMARY SHEET

CASE NUMBER 11

RADAR SHADOW DISPLAY Figure 29

AREA Coffi.: Rocks, Pennsylvania

AIRCRAFT PARAMETERS

POSITION $41^{o}15'$ North Latitude

$77^{o}45'$ West Longitude

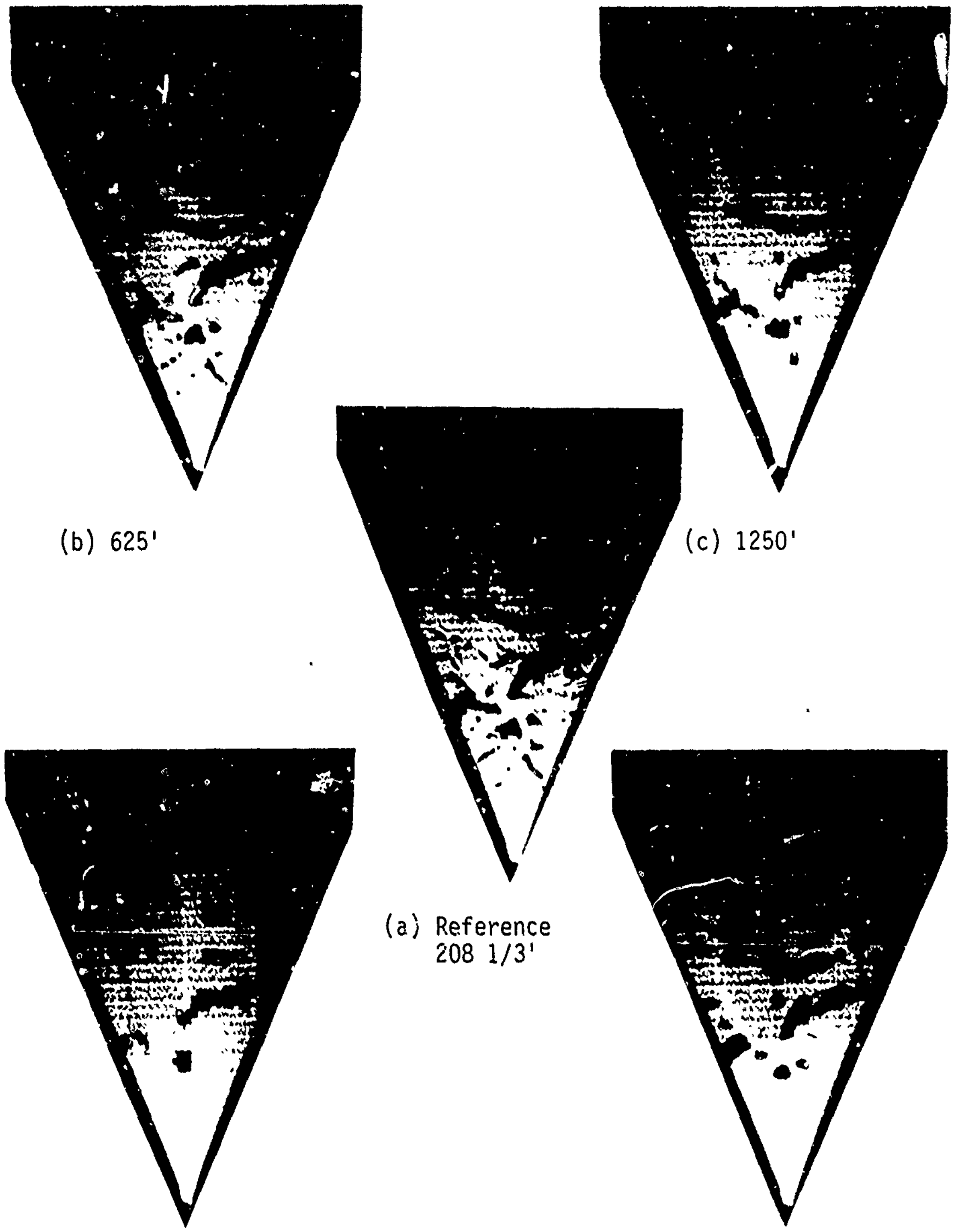
HEADING 90^{o}

ALTITUDE 7000'

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.055855	0.096553	0.113604	0.073621
CONNECTEDNESS	0.038687	0.034543	0.064466	0.322571
SHADOW LOSS	0.086265	0.170583	0.213156	0.125289
SHADOW GAIN	0.032330	0.033893	0.027855	0.030594
NORMALIZED* PERFORMANCE CRITERIA	0.096298	0.158964	0.197415	0.221991

* A combined error measure, scale 0.0 to 1.0



(b) 625'

(c) 1250'

(a) Reference
208 1/3'

(d) 1875'

(e) Modified Lagrange
Polynomial
5000' Regions

FIGURE 29

RADAR SHADOW DISPLAY, COFFIN ROCKS, PA. AIRCRAFT ALTITUDE 7000'

CASE STUDY SUMMARY SHEET

CASE NUMBER 12

RADAR SHADOW DISPLAY Figure 30

AREA Coffin Rocks, Pennsylvania

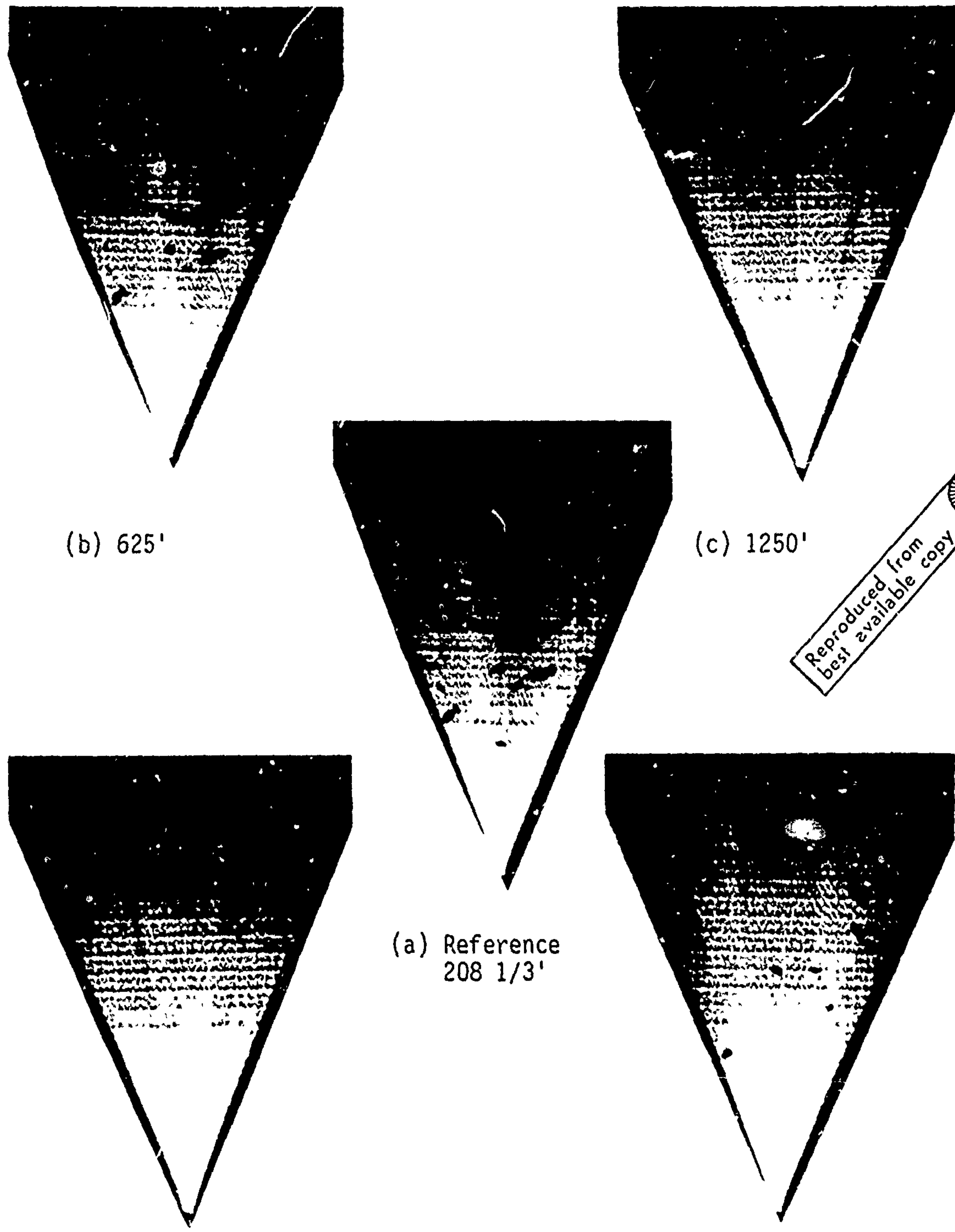
AIRCRAFT PARAMETERS

POSITION	$41^{\circ}15'$	North Latitude
	$77^{\circ}45'$	West Longitude
HEADING	90°	
ALTITUDE	20,000'	

NORMALIZED ERROR MEASURES (Scale 0.0 to 1.0)

DATA BASE	625'	1250'	1875'	Modified Lagrange Polynomial
WEIGHTED ERROR	0.002480	0.003526	0.003853	0.002872
CONNECTEDNESS	0.092207	0.103328	0.304875	0.343104
SHADOW LOSS	0.042168	0.071219	0.081559	0.058854
SHADOW GAIN	0.012731	0.006944	0.004205	0.004207
NORMALIZED* PERFORMANCE CRITERIA	0.050400	0.064083	0.136570	0.141140

* A combined error measure, scale 0.0 to 1.0



(b) 625'

(c) 1250'

(a) Reference
208 1/3'

(d) 1875'

(e) Modified Lagrange
Polynomial
5000' Regions

FIGURE 30

RADAR SHADOW DISPLAY, COFFIN ROCKS, PA. AIRCRAFT ALTITUDE 20,000'

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BIOGRAPHICAL SKETCH

Alexander James Grant was born March 26, 1942, at Bay Shore, New York. In June, 1959, he was graduated from Central Islip High School. In August, 1962, he received the Associates in Applied Science degree from Rochester Institute of Technology. In August, 1964, he received the degree of Bachelor of Science, Electrical Science, from Rochester Institute of Technology. From 1963 to 1964 he worked as an instructor at Rochester Institute of Technology. From 1964 to 1965 he worked for The Liquidometer Corporation, Long Island City, New York. From 1965 to 1968 he was a graduate student at the University of Vermont, receiving a Master of Science in May, 1968. From 1968 to the present time he has been an Electronic Engineer with the U.S. Naval Training Device Center, Orlando, Florida. In 1968 he enrolled in the GENESYS program at the University of Florida.

Alexander James Grant is married and is the father of one child. He is a member of Alpha Pi Mu and the Institute of Electrical and Electronic Engineers.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Engineer.

Barney L. Capehart, Chairman
Assistant Professor of Industrial and Systems Engineering

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E. J. Muth
Associate Professor of Industrial and Systems Engineering

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R. C. Harden
Professor of Electrical Engineering

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James C. Wootton
Director of Research and Technology
U.S. Naval Training Device Center

This thesis was submitted to the Dean of the College of Engineering and to the Graduate Council, and was accepted as partial fulfillment of the requirements for the degree of Engineer.

June, 1972

Dean, College of Engineering

Dean, Graduate School